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Digital approach to AEC synchronous co-located collaboration: use of 4D and Lean planning for collective and interactive decision-making

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Abstract

This research in the domain of Architecture, Engineering and Construction (AEC) focuses on Building Information Modeling and Management (BIM) and multidisciplinary collaboration. Over the past few decades, the industry has supported various changes through digital work tools and technologies. Moreover, advancements in innovative approaches like BIM, Lean Construction (LC) and Integrated Project Delivery (IPD) approaches causing paradigm shifts and transformations of the established ways of design, construction and management. A synergy of these approaches frames the research context.

The research aims to improve the quality of collaboration for AEC professionals, who would benefit from the development of more relevant and efficient tools, protocols and processes. From a broad perspective, there are issues related to each approach's implementation and to their joint implementation, such as lack of experience, established practices, protocols, skills and tools. Integration challenges come from the financial and organizational impacts, as well as that team members come from different work environments. The efficiency of work on digitally developed construction projects requires a new vision and adaptation of collaborative practices. There is a need for well-adapted and integrated digital tools to collaborate on a project.

The study object is the collective use of 4D BIM (3D + time) and Lean scheduling for decision-making. AEC professionals would benefit from the development of efficient tools, protocols, and processes that support BIM/4D continuous accessible dataflow, foster integrated team collaboration, foster the use of 4D and lean planning, and present the team members with accessible and easy interactions with nD.

Our research methodology combines Socio-technical Systems (STS) and Activity theory (AT) and uses the methods of User-centered Design (UCD). Socio-technical systems describe complex environments that use BIM and other digital tools as an intermediary for collaborative work on projects. Activity theory further provides us with tools to describe collaborative activity models. UCD provides usability enhancement methods to improve the effectiveness, efficiency, and usability aspects of collaborative tool and scenarios development. The mixed research methods of observation, questions and interviews allowed for both qualitative and quantitative data. These research hypotheses may be summarized by the following:

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team.*
- *H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration.*
- *H3. A digital tool uniting BIM 4D and Lean scheduling creates a basis for the integration of design and construction dataflows and is perceived by the users as providing a relevant level of information detail for collective decision-making at every phase.*

We propose a digital tool uniting 4D BIM and Lean scheduling that would provide a basis for the integration of the design and construction dataflows and innovative approaches. We examine the context of recent advancements in BIM, Lean construction, and IPD approaches, as well as the 4D BIM uses and their impact on collaboration; then we propose and evaluate a solution providing easy access to relevant digital project information for every project team member. Thus, this research also converges with the domains of Human-Computer Interaction (HCI) and UCD.

Key words: BIM, 4D BIM, 4D BIM uses, Lean construction, Integrated project delivery, synchronous co-located collaboration, collaborative planning, digital continuity, natural user interface, interactivity.

Résumé

Approche numérique à la collaboration synchrone colocalisée dans le domaine de l'architecture, l'ingénierie et de la construction : utilisation de la 4D BIM et de la planification Lean pour une prise de décision collective et interactive

Cette recherche dans le domaine de l'architecture, de l'ingénierie et de la construction (AIC) se concentre sur le Building Information Modeling and Management (BIM) et la collaboration multidisciplinaire. Au cours des dernières décennies, l'industrie a subi divers changements induits par le développement de technologies et d'outils de travail numériques. L'intégration des approches innovantes telles que le BIM, le Lean construction et l'Integrated Project Delivery (IPD) entraînent des changements de paradigme et des transformations des méthodes de conception, de construction et de gestion. Une synergie de ces approches encadre le contexte de notre recherche.

La recherche vise à améliorer la qualité de la collaboration pour les professionnels de l'AIC, qui bénéficieraient du développement d'outils, de protocoles et de processus plus pertinents et efficaces. D'un point de vue général, la mise en œuvre séparée ou conjointe de ces approches, se confronte à quelques difficultés comme le manque d'expérience, de pratiques établies, de protocoles, de compétences et d'outils. Les défis liés à cette mise en œuvre sont à la fois financiers mais aussi organisationnels du fait que les membres de l'équipe viennent d'environnements de travail différents. Pour améliorer l'efficacité du travail réalisé dans les projets de construction développés numériquement, une nouvelle vision et une adaptation des pratiques de collaboration est nécessaire pour disposer d'outils numériques adaptés et intégrés aux pratiques collaboratives du projet.

Notre objet d'étude porte sur l'utilisation collective du BIM 4D (3D + temps) et de la planification Lean pour la prise de décision et le développement d'outils, de protocoles et de processus efficaces accédant à un flux de données BIM/4D en continu favorisant la collaboration intégrée des équipes.

Notre méthodologie de recherche combine les systèmes sociotechniques et la théorie de l'activité et utilise les méthodes de la conception centrée sur l'utilisateur (UCD). Les systèmes sociotechniques décrivent des environnements complexes qui utilisent le BIM et d'autres outils numériques comme intermédiaires pour le travail collaboratif sur des projets. La théorie de l'activité nous fournit des outils pour décrire des modèles d'activités collaboratives. L'UCD fournit des méthodes d'amélioration de l'utilisabilité des outils proposés par l'exploitation de scénarios collaboratifs. Les méthodes de recherche mixtes (observation, questions et entretiens) ont permis d'obtenir des données qualitatives et quantitatives.

C'est dans ce cadre méthodologique que nous avons formulées les hypothèses suivantes :

- *La collaboration numérique synchrone colocalisée pour la prise de décision serait perçue par les membres de l'équipe de projet comme améliorant la collaboration et l'intégration de l'équipe.*
- *H2. L'utilisation d'un support numérique avec une visualisation nD de qualité et une interface d'interaction naturelle pour la prise de décision collective serait perçue par les membres de l'équipe de projet comme utile à la collaboration.*
- *H3. Un outil numérique unissant le BIM 4D et le Lean scheduling crée une base pour l'intégration des flux de données de conception et de construction et est perçu par les utilisateurs comme fournissant un niveau pertinent de détail des informations pour la prise de décision collective à chaque phase.*

Nous proposons un outil numérique unissant le BIM 4D et Lean construction qui fournirait une base pour l'intégration des flux de données de conception et de construction et des approches innovantes. Nous examinons le contexte des récentes avancées en matière de BIM, de construction Lean et d'approches IPD, ainsi que les utilisations de la BIM 4D et leur impact sur la collaboration ; puis nous proposons et évaluons une solution permettant à chaque membre de l'équipe de projet d'accéder facilement aux informations numériques pertinentes du projet. Subséquemment, cette recherche converge également avec les domaines de l'Interaction Homme-machine (IHM) et du Design centré utilisateur (UCD).

Mots clés : *BIM, BIM 4D, usages du BIM 4D, Lean construction, Integrated Project Delivery, collaboration synchrone colocalisée, planification collaborative, continuité numérique, interface utilisateur naturelle, interactivité.*

Le chapitre 1 est intitulé “ Revue de l'utilisation de BIM/4D, de Lean construction et de Integrated project delivery (IPD) dans des projets de construction pour la collaboration”. Ce chapitre décrit un contexte complexe d'interactions entre la technologie, les personnes et les processus, et établit une base pour notre recherche. Tout d'abord, il résume les changements et les avancements liés à l'utilisation du numérique et le développement du BIM, ainsi que la nécessité d'un échange des données du projet plus efficace et d'une meilleure interopérabilité. Le sujet de recherche est centré sur les questions liées au BIM 4D et à la gestion du planning de construction. Deuxièmement, le chapitre décrit le rôle de la collaboration dans le secteur d'AIC, et sa place dans un système sociotechnique. Il décrit également les moyens d'aborder la gestion de projet et le planning de la construction de manière plus collaborative, plus efficace et visant une plus-value du projet pour le client, comme l'IPD et Lean construction. Le chapitre est achevé avec le résumé de la synergie BIM/4D avec l'IPD et de Lean construction. Cela établit une base théorique pour l'analyse de la collaboration et la 4D, ainsi que des exigences pour l'utilisation du BIM 4D et Lean construction management.

La diffusion des outils numériques de modélisation et de gestion de l'information sur les bâtiments BIM a favorisé divers progrès et défis dans le secteur de l'architecture et de l'ingénierie. En outre, les méthodes de planification de la construction et de la gestion du projet progressent en mettant l'accent sur l'optimisation, la numérisation, la collaboration et l'intégration. L'émergence de nouveaux outils, comme toute innovation, aspire à de nouvelles utilisations en apportant des solutions aux problèmes existants ou en offrant de nouvelles fonctionnalités. Cependant, de nouvelles exigences, usages et défis émergent également. Les outils innovants proposent des solutions à des problèmes existants ou des nouvelles fonctionnalités.

La mise en place du BIM met les modèles intelligents ND au cœur technique d'un système sociotechnique. Ce cœur est englobé par les aspects sociaux, notamment la collaboration synchrone, les pratiques coordonnées et la culture institutionnelle. Outre les divers avantages pour un projet, une mise en place d'usage du BIM nécessite une continuité des informations numériques, l'interopérabilité des données pour la conception collaborative et pour éviter les pertes de données, ainsi que des flux de travail et des protocoles pour organiser le travail et la collaboration.

Les nouvelles méthodes de planification et de gestion de la construction, parallèlement au développement du BIM, ont également apporté diverses innovations et avantages à l'AIC. Le développement et la mise en œuvre de Lean construction a apporté divers avantages en répondant aux besoins d'une planification plus efficace, d'une programmation basée sur l'emplacement des processus et d'un contrôle des pertes. En outre, ils ont répondu au besoin d'une prise de décision plus collaborative et intégrée, et de l'intégration de l'expertise de chaque membre de l'équipe depuis les premières étapes du développement du projet jusqu'à sa livraison. Cependant, étant donné la base

historique mis sur les activités de construction, l'usage de Lean construction reste limité pendant la conception et ne bénéficie pas toujours de BIM, ni de la méthode de l'IPD.

Les méthodes émergentes de réalisation de projets plus collaboratives et intégrées, telles que Bid-Build ou d'IPD, permettent d'accroître l'efficacité de la communication et de la collaboration, d'améliorer les délais, les coûts et le contrôle des déchets. Avec de telles approches, les équipes, la technologie et les processus sont intégrés dans un système holistique et se concentrent sur un objectif commun. Cependant, ces approches présentent des défis en raison de leur complexité et de la nécessité d'élaborer des réglementations pertinentes, ainsi que de structurer le flux de travail, l'environnement de collaboration et de s'écarter des pratiques courantes. En outre, elles reposent sur l'utilisation d'outils numériques tels que le BIM et les supports interactifs pour la conception et la prise de décision.

Le BIM 4D a de multiples usages et représente un support utile non seulement pour la conception de projets, mais aussi pour les simulations, l'analyse, la gestion et la prise de décision en matière de construction, quelle que soit la phase du projet. Cependant, l'utilisation du BIM 4D pour la planification et la prise de décision collectives reste limitée pour plusieurs raisons. Premièrement, cela est dû à la nature des informations BIM 4D qui rend difficile la visualisation des informations complexes. Deuxièmement, en raison des compétences professionnelles sous-optimales pour l'adoption d'un changement de paradigme vers un travail plus collaboratif. Troisièmement, en raison du manque de méthodes et d'outils permettant l'utilisation du BIM 4D pour la collaboration et pour la prise de décision.

Les approches BIM, Lean construction et IPD bénéficient de leur usage conjoint et se complètent mutuellement. En outre, elles valorisent toutes une collaboration efficace comme une activité essentielle à la réussite du projet. Une telle mise en œuvre fonctionne comme la combinaison d'idées représentant des personnes - IPD, des processus - Lean construction, et des outils BIM. Cependant, il manque une approche holistique permettant leur synergie. En dépit d'un développement dynamique, les outils, les méthodes et les cadres qui favorisent la synergie restent limités. Les outils BIM 4D et de Lean construction permettant une planification collaborative pour aider l'équipe intégrée restent également limités.

Le chapitre 2 est intitulé "La méthode de recherche et l'identification des exigences pour une collaboration basée sur la 4D". Ce chapitre décrit les méthodes d'études de la collaboration et les technologies. Il identifie les pratiques et les besoins des utilisateurs, ainsi des approches et des outils numériques disponibles. L'identification permet de recueillir les exigences de collaboration et d'utilisation du BIM 4D pour une proposition de scénarios et de prototype d'outil numérique pour assister à la collaboration basée sur la 4D. Les solutions commerciales et de recherche pour l'usage de BIM 4D et du Lean ont été développées pour répondre aux demandes de l'industrie en matière d'interopérabilité, de modélisation, de planification, de détection des collisions et de gestion de la production de la construction. Cependant, leur conception et leurs caractéristiques principales ne permettent pas toujours la mise en œuvre efficace des utilisations du BIM 4D, l'intégration des données, ni ne fournissent pas des interfaces pour la prise de décision interactive et collective. Les exigences relatives aux outils évoluent en même temps que l'évolution des approches AEC. Ce chapitre se termine par la mise en évidence des exigences relatives aux outils de collaboration basés sur la 4D et aux interactions avec les utilisateurs.

Le chapitre 3 est intitulé "Expérimentation sur l'utilisation de BIM/4D et NUI pour la collaboration synchrone et la prise de décisions". Ce chapitre présente les résultats d'expérimentation dans un contexte pédagogique qui étudie la collaboration numérique synchrone colocalisée pour identifier les exigences et pour améliorer la qualité de la collaboration, l'utilisation de BIM/4D, la planification

collective du projet et les interactions avec l'interface naturelle. Dans ce contexte pédagogique, nous avons pu évaluer la facilité d'utilisation d'une table numérique tactile pour la collaboration du point de vue d'utilisateurs habitués qui s'en servent dans le contexte des projets de construction réels (petites structures en bois). Ainsi, nous avons pu décrire les interactions des utilisateurs avec les documents numériques de projet lors des sessions de collaboration. Dans notre étude, les interactions des utilisateurs avec la table ont été classées en trois catégories : visualisation, manipulations et annotations.

Les utilisateurs ont manipulé des modèles 3D/4D pour la présentation du projet et ont annoté les documents pour enregistrer la décision de collaboration. Les croquis et les annotations ont été utilisés pour soutenir les solutions aux problèmes identifiés et pour suggérer des modifications. Naturellement, les utilisateurs accompagnent leur session de discussions, de pointage et de gestes de mimétisme. La plupart des équipes d'étudiants ont quitté la session avec un grand nombre de commentaires non structurés car ils ne mettraient pas naturellement en œuvre des pratiques de collaboration efficaces.

L'activité collaborative analysée montre que le modèle 3D est principalement au centre de la discussion et nécessite donc une interaction facile et naturelle. En outre, les utilisateurs ont eu tendance à résoudre toutes les questions avec un seul document comme support de décision. Par conséquent, l'unification de toutes les informations du projet dans un même noyau numérique peut s'avérer bénéfique non seulement pour la continuité du flux de données numériques, mais aussi pour une collaboration plus interactive.

Le chapitre 4 est intitulé "Proposition de scénarios pour la prise de décision collaborative colocalisée assisté par le BIM". Ce chapitre présente les propositions relatives à l'identification des types de collaboration et des persona utilisateur pour les groupes de collaboration, ainsi qu'une proposition de mise en œuvre d'usage de BIM 4D et de Lean planification dans des scénarios de collaboration assisté par les supports numériques.

La complexité des projets et des activités de collaboration exige une conceptualisation claire des processus de prise de décision, des rôles de chaque membre de l'équipe de projet ainsi que la nature des décisions. Par conséquent, nous identifions des persona utilisateur d'un groupe de collaboration, des types de prise de décision et des rôles des membres de l'équipe.

La mise en œuvre des persona de groupe de collaboration permet de prendre en compte les différents rôles des acteurs tout au long du processus de collaboration pour la conception d'un outil numérique. Chaque type est décrit par des dimensions : objectifs, tâches et motivation du groupe ; membres du groupe ; style de travail et style de leadership, etc. L'utilisation de la BIM 4D serait pertinente pour la médiation de différentes situations de collaboration. Les groupes de collaboration peuvent impliquer diverses utilisations de la BIM 4D en fonction de la phase d'avancement du projet. Par exemple, l'équipe de conception du projet peut utiliser la planification et la détection des conflits en 4D. L'équipe de construction peut bénéficier de la visualisation 4D pour une meilleure communication.

Le Chapitre 5 est intitulé "Prototypage et évaluation de l'outil "4D Lean Board". Ce chapitre continue à présenter les propositions de recherche. D'abord, il décrit notre contexte de prototypage. L'association avec le contexte de recherche du projet 4DCollab, nous a permis de bénéficier de l'expertise de l'équipe de recherche multidisciplinaire. Bien que les deux études partagent des objectifs, des enquêtes et des résultats d'expériences similaires, les résultats du prototypage se concentrent sur les différents aspects de la collaboration, puisque nous avons exploré la visualisation du planning Lean.

Ensuite le chapitre présente une interface d'application web "4D Lean Board" et de ces fonctionnalités pour la collaboration synchrone assisté par le BIM 4D et Lean planification. Le développement et les évaluations du prototype de "4D Lean Board" ont été structurés selon des catégories abordant différents niveaux de STS : collaboration numérique synchrone en colocalisation ; environnement de collaboration numérique ; BIM 4D et utilisation Lean ; évaluations de la conception et des interactions.

Enfin, une description des évaluations du prototype et un résumé des commentaires des utilisateurs, concluent l'évaluation des propositions. D'après les commentaires et les observations des utilisateurs, l'environnement de collaboration numérique avec une visualisation 3D de qualité et une interface d'interactions naturelles a été perçu par les utilisateurs comme un moyen utile et efficace d'améliorer la collaboration. La collaboration numérique synchrone en colocalisation s'est avérée également plus interactive et démocratique. Ainsi, la mise en œuvre conjointe de BIM 4D et de Lean planification a permis aux professionnels de l'AIC de bénéficier non seulement d'une visualisation efficace comme un outil assistant à la collaboration, mais aussi d'un outil de collaboration plus engagé et interactif. Les niveaux de planification et les exigences des tâches ont été perçus comme des outils efficaces pour communiquer la planification du projet, et comme efficaces pour la gestion de la construction.

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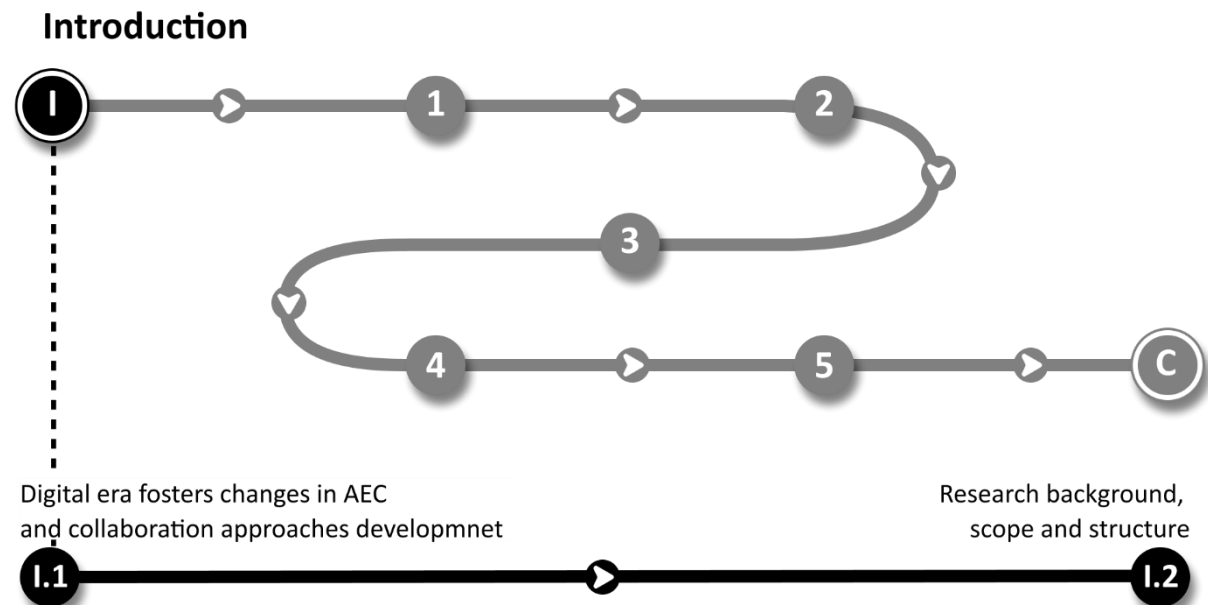
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Introduction. Context of BIM collaboration and a need for tools fostering efficient decision-making

The present work is set in a multidisciplinary setting, at the crossroads of digital tools, collaboration, and innovative management development. Thus, the following introduction outlines relevant shifts in construction practices, research results that exist as well as questions and challenges that we were seeking to solve in our work.

Structurally, within this outline, first, the introduction emphasizes changes in AEC fostered by the digital era. Second, it highlights an importance of communication and efficient collaboration in a project workflow. Then we proceed with introducing innovative project management concepts (I.1) as a general context of this research and to present a basis for the research design. Next, the introduction outlines the research background to account for the previous studies related to the local research at the MAP-CRAI laboratory. Further, it sets the scope of the research and, to conclude, describes the thesis structure by chapters (I.2).



I.1. Digital era fosters changes in AEC and collaboration approaches

I.1

I.2

Digital era and AEC industry

Digitalization, innovation, interconnection tendencies and rapid progress of information and communication technologies bring major shifts into all industries, including the Architecture, Engineering and Construction (AEC). Such progress within the industry fosters development of new approaches of digital projects management and more globalized work approaches. During the last decades, the industry has endorsed various changes brought in by the digital work tools and technologies, by CAD, by the *adoption of Building Information Modeling/Management (BIM) and by new digital practices*. Thus, the common practices of design, construction and management must adapt to these changes and develop a new vision, provide efficient tools for working on digitally developed projects.

The establishment of project design and construction practices has a long history. Yet, the recent technology progress introduces a *digital-age shift and challenges* to AEC industry's established ways of design and construction. The established practices had to evolve, as project design was transferred not only to a digital sheet, but also to a digital virtual 3D model. The shift pushes back previous limitations of project design and favors the proposal of well-thought complex and ingenious designs.

Currently, most AEC professionals develop their projects with the help of digital tools and practices. However, not all of them have yet fully integrated the use of 3D semantically enriched models, which are fundamental for the BIM project management and design methods (Delcambre, 2014). Additionally, BIM projects reveal an advantage of *improved exchanges, communication, and coordination* within the project due to the possibility to interact with the 3D model content (Succar, 2013). Therefore, on top of being efficient at satisfying old needs, modern design, construction and management tools open a way to *new aims which cannot be achieved from conventional approach angles*.

Collaboration role in project design and construction

In most cases the design and construction *project is unlike any other*, due to its specific location, project program elements, design, available resources, environment, project design and construction teams, etc. Therefore, these factors create a unique set of conditions, tasks, and challenges from project to project which must be met by design and construction.

A delivery of an AEC project is usually due to a team effort of many professionals. Within the digital era, the project digital models' complexity of development involves diverse AEC professionals in collaborative practices. Due to the complexity of the design and management of projects, and to the number of professionals from various disciplines involved into the project, *communication and information exchanges* around the project have a direct influence on the *efficiency of the work and the quality of the project* (Guerriero and Gronier, 2014) (Himmelman, 2004).

Furthermore, the three-dimensional representation opens a possibility to run 4D BIM (time, schedule, evolution) simulations. The model passes to the next BIM level, where the processes are

included into the model data. *The model is collaborative, and it offers a path for other numerous nD BIMⁱ simulations*, such as: coasts, energy requirements, sustainability, life cycle analytics, etc. (Boton, 2013)(Halin et al., 2012). Such numerous information and simulations offer AEC professionals to work not only with a BIM model, but eventually with a digital twin of a construction project. As such a modernization of the current practices aims *to simplify the collaboration and work methods and to improve the project quality* (Kvan, 1998). It also faces several adoption and implementation barriers, which brings various challenges.

Information exchanges, communication and collaboration on a project represent social parts of a socio-technical system, and they encompass digital management and BIM in the system's core. Thus, *following the shift towards BIM and digital tools* for design and management, there is a *need for well-adapted and integrated digital tools to collaborate on a project*. Such collaboration tools must allow efficient exchanges, interoperability, and accessibility for all team members, and they also must *ensure the digital workflow continuity*.

Innovations in project management

Following design and construction, project management methods also have a history of advancements. The shift to the use of *BIM fosters the evolution of the existing project and construction management approaches*, which may include the tasks of digitally based collaboration, of optimization and avoidance of waste, or which may emphasize the focus on the value for the owner, on sustainability and preservation of the environment. The adoption of BIM even fostered cooperation of AEC and Facility Management (FM) (Caramia et al., 2021), and it extended the use of BIM models and simulations to FM, or it promoted an implication of future actors into decision-making on the project.

The project management approach of *Integrated Project Delivery (IPD)* emerges to enhance the *BIM-based collaboration and benefits* (AIA, 2007). It creates more cohesive collaboration inside the project team than linear design-bid-build approaches, outlines the digital workflows and protocols, aims to clearly outline and then to respect project requirements, schedules, and costs. Such an approach has already been evaluated and adopted by various professionals worldwide. However, since IPD is dependent on the legal context, the owner's agenda and on the level of BIM adoption by the available project team members, its use is yet limited. In addition, *Lean construction* techniques of waste removal continue the idea of a focus on more cohesive collaboration and on a better efficiency to manage construction work and value delivery (Sacks, Korb, et al., 2017).

IPD and Lean Construction represent *progress and innovation* in the project management and construction management. They unite the BIM and digital tools, the project team, and the process into elements of one system for efficient project delivery. They also *transform the existing ways of collaboration and generate needs for new digital tools and methods of design and decision-making*.

A synergy of IPD, BIM and Lean construction approaches, which together organize the processes, technology and professionals improve effectiveness (Machado et al., 2020), yet they require adjustments and balance (Sacks, Koskela, et al., 2010).

ⁱ nD BIM representing different extensions to the 3D dimension of BIM model, encompassing 4D BIM combining 3D and schedule information, 5D adding costs to the 3D model, etc.

I.2. Research background, scope, and structure

I.1

I.2

Research background

“Collective activities and digital models” is one of three major research axes of UMR 3495 MAP-CRAI research laboratory. Since 2002, several PhD theses have contributed to the development of knowledge in this research axis. They establish a continuity of local research on the subject of collective activity in AEC and digital models uses.

One of such theses is the one by Sylvain Kubicki *“Assisting flexible coordination of building construction activity. A model-based approach for proposing tools for visualizing the cooperation context.”* (Kubicki, 2006a), proposing a study of collective activities organization during design and construction phases. S. Kubicki described the collective activity in terms of *protocols and static or dynamic artefacts* to propose scenarios of 4D uses and presented a proposal of a prototype where he *adjusted the displayed views to the user types*; he also stressed the need for relevant tools, such as a server, a 4D tool, a control board, and a reporting tool.

Next, the thesis by Annie Guerriero *“The representation of trust in collective activity. Application to the coordination of construction site activity.”* (Guerriero, 2009) investigated the concept of trust in AEC, analyzed the tools used for construction administration, and presented a proposal of a *prototype of dashboard* for management of a construction site activity with improved trust.

With the following thesis *“Design of domain views in service-oriented groupware. Towards multi-views adapted for collaborative 4D/nD construction simulation.”* (Boton, 2013). Conrad Boton continues the investigation on collaboration practices and situations, the roles of different project stakeholders at project meetings and the use of 4D/nD, as well as the need for adaptation of *interactivity and of information representation “views”* to a collaboration situation.

Finally, the thesis *“Designing collaborative services adapted to business practices: a user-centered method. Application to the construction field.”* (Zignale, 2013) by Daniel Zignale also investigates collaboration practices and situations and proposes user personas and an *approach of user-centered design* for collaboration tools prototyping.

These works have explored several theories describing group activities, collaboration, and business processes; they have also analyzed collaborative activity in a scope of different needs according to particular collaboration situations, proposed some 4D prototypes or dashboard prototypes. Thus, some elements of these different works present us with useful experience, proposals, and background for our research.

Moreover, this thesis work was developed as a part of an international research project *“4D Collab”*¹: usage and interaction of synchronous 4D simulation for collaborative decision support in Architecture, Engineering and Construction. It was cofounded by national research agencies: ANR-16-CE10-0006-01 in France ², and FNR 11237662 in Luxembourg³.

Also, the thesis was written under a supervision of Dr Gilles Halin at the research laboratory *“Mixed Research Unit 3495 Models and Simulations for Architecture and Heritage”*⁴ (UMR 3495 MAP-CRAI), located at National School of Architecture in Nancy⁵ (ENSAN), France, and Dr Annie Guerriero (LIST -

Luxembourg Institute of Science and Technology, Esch-sur-Alzette, Luxembourg), both are members of the 4DCollab research project team.

The thesis and 4DCollab research subjects are naturally aligned as both studies investigate co-located synchronous *collaboration, the use of 4D BIM and natural user interaction supports*. The 4DCollab research project objectives were to:

- measure the added value of 4D BIM use *on pre-construction phase of a construction project*.
- study and describe 4D-based collaborative work practices and use of emerging digital collaborative devices through a user-centered approach and cognitive ergonomics.
- prototype a 4D-based collaboration tool *enabling user's interactions with 4D through a digital collaboration table*.
- validate the collaborative 4D uses *and to identify the added value to a construction project team*.

The 4D Collab objectives, resources and timeline are broader than the objectives of this thesis. However, they both *mutually benefit from the research findings*. The 4DCollab analysis of the use of 4D BIM presents us with a better understanding of the current 4D BIM use context, practices, and limitations (**Error! Reference source not found.**). Also, the 4DCollab team had an opportunity to evaluate AEC professionals collaboration with 4D and natural interaction mediums (touch screens and collaboration software), which provides valuable feedback on collaboration and user needs for 4D-based tool prototyping.

The following thesis chapters describe in more detail the connection and application of 4DCollab project findings (5.1.1). However, to shortly describe some differences: with this thesis we had an opportunity to diverge from the 4D Collab by broadening the scope to the design development and construction stages and exploring integrated scheduling implementation. We also had an opportunity to expand users' feedback with the observations of students' collaboration (3.1), and finally we explore the use of lean principles for a 4D-based collaboration tool prototype.

Research scope

Shift of the paradigm by innovative approaches for design, construction, and management

Novel tools, methods and approaches emerged in past decades to foster more efficient, collaborative, and complex delivery of projects. Various advancements brought by innovative approaches like *BIM, Lean construction and integrated project delivery approaches are now causing paradigm shifts* and transformations of the established ways of design, construction, and management. Naturally, each of them focuses on aspects and purposes concerning technology, processes, or people. Yet, they share several common goals as well, and their joint implementation is beneficial and recommended. However, due to the novelty and complexity, lack of established protocols and knowledge basis, to the continuous improvement of the tools and uses, *their efficient synergetic implementation is still in development*, and stays relatively limited.

Essential role of collaboration in project success

Due to the complexity of design, construction, and management of AEC projects, and to the number of various disciplines and professionals involved into a project development, project teams would be inevitably brought to work together with a different level of interactions. Thus, the quality of

communication and exchanges between the team members influence work efficiency and impact the outcomes. However, every construction project is unique. The project teams are likely to differ from project to project, *to establish new collaboration environment, implement tools and protocols, structure the organization and interactions*. Digitally based project design and management rely on specific tools. With BIM the tools are in the core of a socio-technical system, and they are managed by social elements: synchronous collaboration, coordinated work practices, institutional and cultural frameworks (Sackey, 2014). BIM and intelligent models bring a variety of benefits, yet they also require relevant tools and protocols to support collaboration.

BIM/4D implementation benefits and collaboration basis

CAD models, BIM, nD BIM and Digital twins—all place the models in the core of project design, construction, and facility management. The use of such advancements requires for a variety of adjustments, development of new practices and skills, establishment of regulations and protocols, implementation of relevant digital tools. Facing such challenges, the implementation of BIM beyond the 3D stays limited. With the implementation of 4D the complexity of data, required skills and possibilities of uses increases, and may present challenges to the users. However, 4D is an example of combination of not only “space” and “time” dimensions, but of distinct *core purposes united in a 4D model/simulation encompassing the results of design efforts, and of construction planning and management efforts*. Thus, it *creates a common ground for closer collaboration* of different disciplines and roles, for emergence of integration of various approaches like BIM and Lean Construction, and for more integrated teams.

Towards digital continuity, integrated and interactive systems, and holistic approaches

Despite the implementation of BIM-based design, in practice, at meetings project design and construction teams often use simpler 2D documents or single user accessible 3D models as mediums for decision-making and collaboration. Such an approach does not maintain the digital continuity of project data, as decisions and discussion are held “outside” the BIM core. This may result in data losses, mistakes, and redundancy of activities. In addition, such usage does not offer all team members a possibility to easily interact with project data, limiting inputs of knowledge, experience, and collaborative efforts. Yet, current technology advancements offer a possibility to preserve the continuity of project data before, during and after the meetings without data losses and to evolve towards automated decision recordings. Moreover, an access to nD BIM data and interactions for all members of a project team is possible when *technologies take their place in the collaborative core of a system*. However, the use of digital tools stays single user-oriented and does not offer easy and democratic interactions, nor does it foster integration of lean construction or integrated project management. The use of digital mediums at project meetings concerning *BIM/4D projects could lead to a collaborative environment configuration that creates a digital collaboration workspace and enhances the collaborative and integrated protocols*. As for mediums featuring natural interaction interfaces, they would foster collaboration through interactivity.

Digital approach to AEC synchronous collaboration

Our main research scope is on *exploration of an approach for collaboration with digital interactive tools and innovative project delivery methods*, with a particular focus on *4D BIM and Lean scheduling collective use for decision-making*. The research seeks to investigate and improve collaboration quality for AEC professionals, who would benefit from a development of the efficient tools, protocols, and processes which:

- support BIM/4D continuous accessible dataflow,
- foster integrated teams collaboration,
- foster use of 4D and lean planning,
- present the team members with an access and easy interactions with nD,
- adjust the collaboration environment and interface to specific meetings, phases, actors, and processes.

In summary, the following barriers establish a departure point for our research (Figure 1), and contribute to the research method structure and ultimately influence the results (Chapter 1):

- *Barrier 1 (B1). Limited BIM and 4D use for decision-making and co-located synchronous collaboration.*
- *Barrier 2 (B2). Need for efficient time management and integrated collaboration, with continuous data and workflow, relevant data visualization and interactions.*
- *Barrier 3 (B3). Lack of synergy in approaches; Lean construction tools have not yet fully emerged with BIM to enable digital collaboration for an integrated team.*

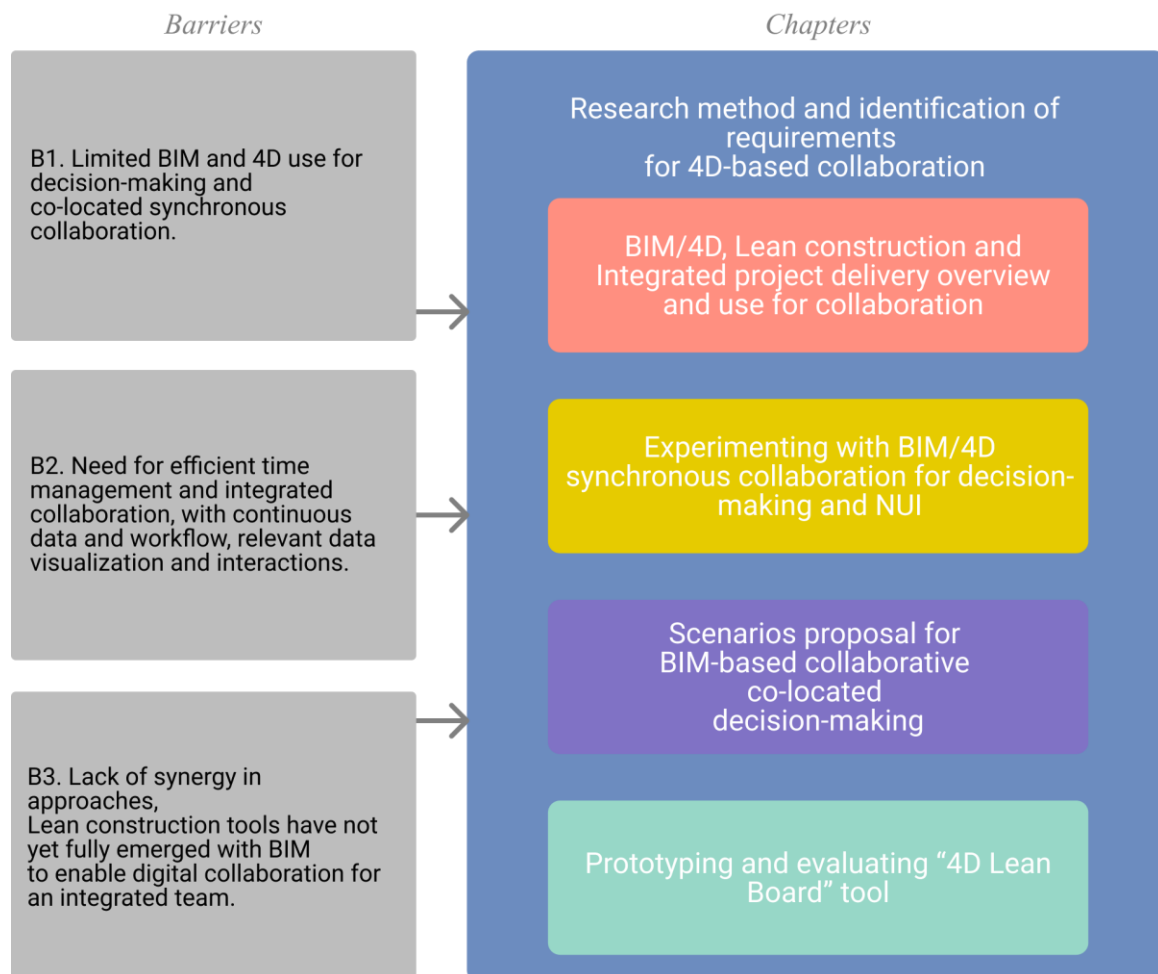


Figure 1. Summary of research barriers and chapters

This research investigation considers the *tools, people and processes* origins of BIM, Lean Construction and Integrated Project Delivery implementation (Figure 2), as a holistic approach, enhancing multidisciplinary *collaboration and integration, fostering BIM and Lean Construction tools implementation*, where the preliminary hypotheses can be summarized by following:

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team.*
- *H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration.*
- *H3. A digital tool uniting BIM 4D and Lean scheduling creates a basis for the integration of design and construction dataflows, and is perceived by the users as providing a relevant level of information detail for collective decision-making at every phase.*

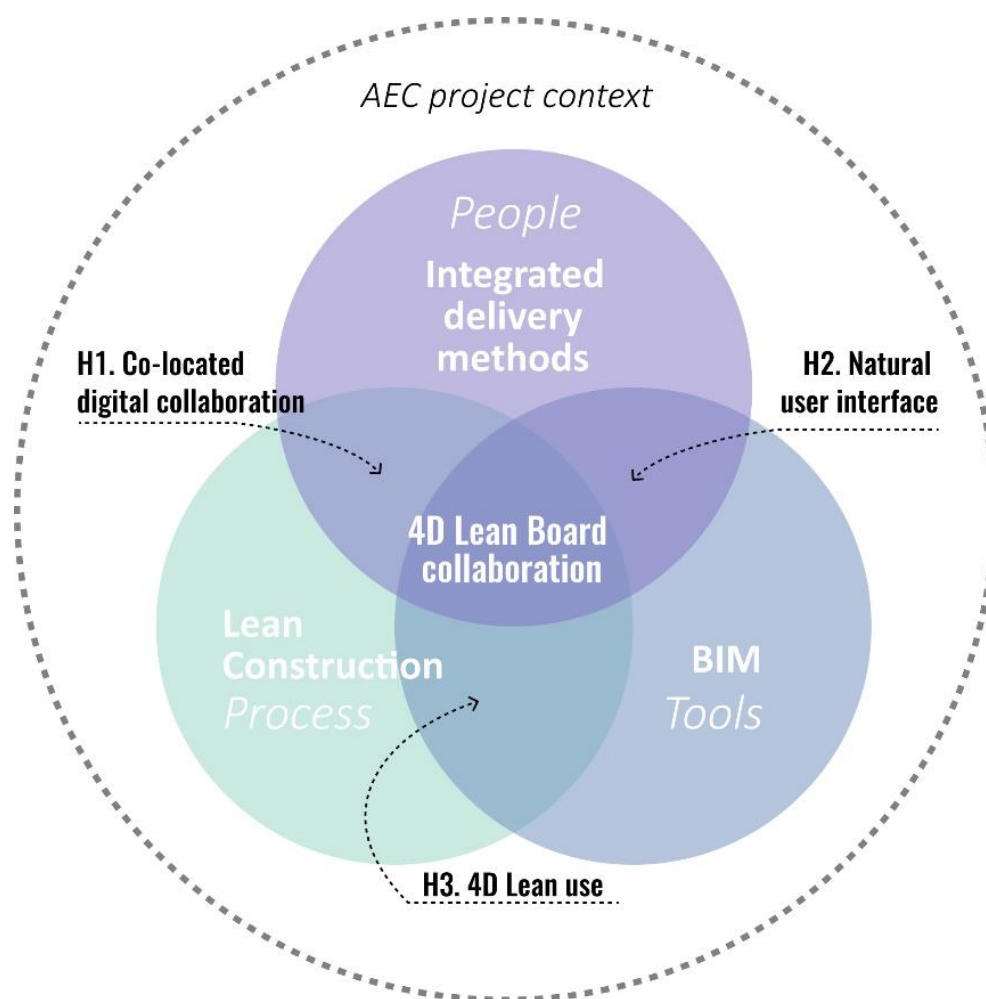


Figure 2. IPD, BIM and Lean Construction approaches connection in organization of a AEC project

Thus, the research develops collaboration scenarios (protocols) and tools (prototype of a digital collaborating environment) with a multi-user digital interaction interface, which will complete a digital continuity of project documents at decision-making sessions, with an aim to avoid printing documents and primarily to keep the same BIM model in the center of discussions as well as in the center of design development. The solution aims to avoid incorrect interpretation and loss of information. For users' comfort it is important to offer the best usability and relevant interactions.

Furthermore, the research scope encompasses following goals:

- *Examine the recent advancements in digital project design and management, in Lean construction, in collaboration and integrated approaches to project delivery.*
- *Examine and explore BIM/4D uses, to outline their collaborative use benefits and requirements, in perspective of their integration into a 4D-based collaborative solution for collective decision-making.*
- *Examine and explore Lean Construction planning tools in perspective of their integration into a 4D-based collaborative solution for collective decision-making.*
- *Study collaboration and project meetings (collaborative sessions), and the use of digital project documents supports with natural user interfaces through experiments.*
- *Identify the requirements for a 4D-based collaborative solution for collective decision-making.*
- *Propose a solution providing an easy access to relevant information for every project team member through collaboration scenarios, prototype and evaluation of a 4D Lean collaboration.*

Thesis structure

After the Introduction, the thesis entails five major chapters (Figure 3), and is organized as follows:

Chapter 1.

BIM/4D, Lean construction and Integrated project delivery overview and use for collaboration:

The chapter portrays a complex context of technology, people, and processes interactions, and establish a basis for the research. First, it highlights the changes and advancements fostered by digitalization and BIM development and the need for more efficient exchange of project data and improved interoperability. The scope is focused on issues related to 4D BIM and construction schedule management (1.1). Second, the chapter outlines the role of collaboration in AEC, and its place in a Socio-technical system. It also outlines the ways to approach the project management and construction scheduling in more collaborative, efficient and value-focused ways like IPD and Lean construction (1.2). The chapter concludes with a review of BIM/4D synergy with IPD and Lean Construction (1.3), which provides a theoretical basis for collaboration analysis and 4D and the requirements for 4D BIM and Lean scheduling use (future results 1-3).

Chapter 2.

Research method and identification of requirements for 4D-based collaboration:

The chapter outlines the research approaches focusing on collaboration and technology studies. It lists existing practices, tools, and user needs, together with the gaps in already present approaches and in available digital tools (2.1). The identification supports the gathering of collaboration and 4D BIM use requirements for a proposal of 4D-based collaboration scenarios and prototype. Further, the chapter outlines the research method and introduces approaches and theories supporting the research (2.1), (future results 1-4).

Chapter 3.

Experimenting with BIM/4D and NUI use for synchronous collaboration and decision-making

The chapter presents the results of digital synchronous co-located collaboration experiments with an aim to identify requirements for improved collaboration, BIM/4D use, collective planning and natural interface interactions. It emphasizes the outcomes of a 3D and 4D based synchronous collaboration experiment with the students during their work on a project in groups (future results 1, 3).

Chapter 4.

Scenarios proposal for BIM based collaborative co-located decision-making

The chapter introduces the research proposals of identification of collaboration types and collaboration group personas, as well as a proposal of 4D BIM and Lean implementation at digitally mediated collaboration scenarios (future results 3, 4).

Chapter 5.

Prototyping and evaluating “4D Lean Board” tool

The chapter continues to present the research proposals, it describes our prototyping context and presents a one-page web application interface and features for synchronous collaboration with 4D and Lean (5.1). Finally, a description of the prototype evaluations and a summary from the user’s feedback (5.2), conclude the proposals outline (future results 3, 4).

Conclusions: emphasize the results of thesis research with a summary of findings and outcomes. They also outline limitations of the study and suggests perspectives for future research and development.

Digital approach to AEC synchronous collaboration: use of 4D and Lean planning for collective and interactive decision-making

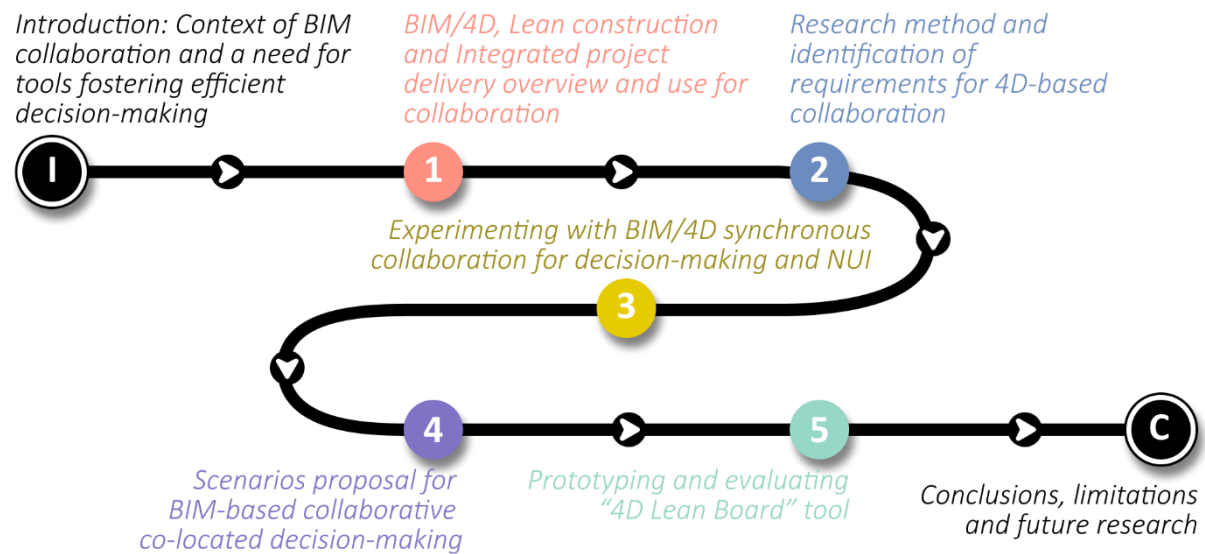


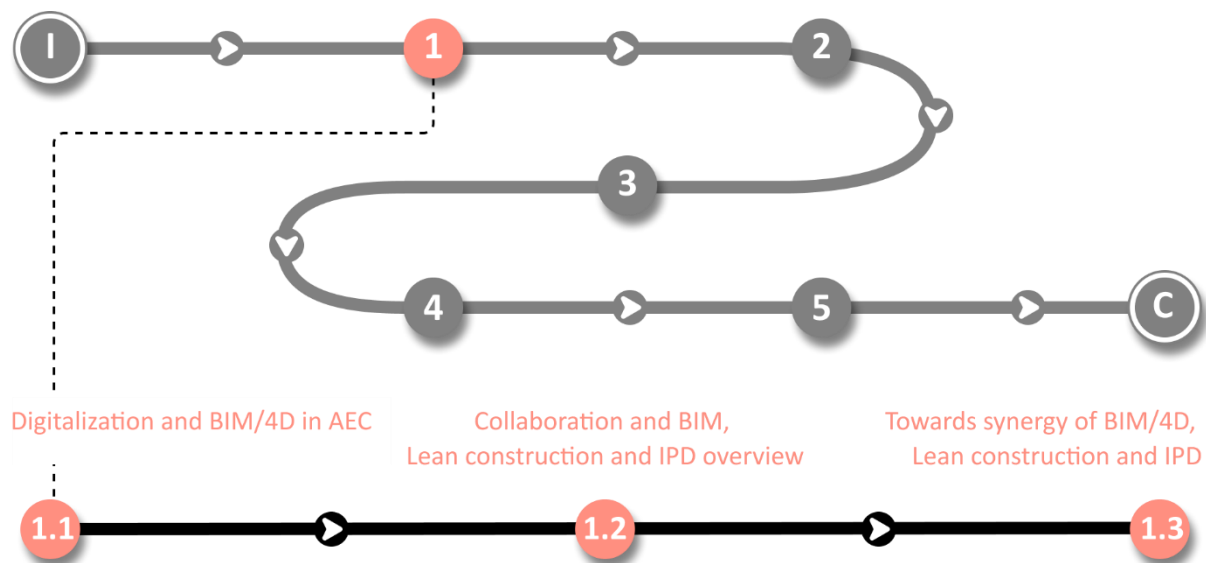
Figure 3. Schema of the research structure and chapters sequence

Chapter 1.

BIM/4D, Lean construction and Integrated project delivery overview and use for collaboration

The following chapter presents a literature review portraying the comprehensive context of implementation of three different approaches impacting efficient project delivery. Such context encompasses various concepts which influence collaboration in AEC. Our main research subject is collaboration with digital tools and innovative project delivery methods, with a specific focus on 4D BIM and Lean planning applications for co-located synchronous collaboration for decision-making.

The review first emphasizes a shift brought by digital tool adoption and by requirements for more efficient project data exchanges and enhanced interoperability, it also describes the evolution of BIM and 4D, and their core place in project design and construction coordination, as a technical core of a socio-technical system (1.1). Next, the chapter reviews collaboration and BIM features in AEC, and the novel innovative and more collaborative approaches of Integrated Project Delivery (IPD) and Lean construction (1.2). The review highlights the context of collaboration, as well as presenting the concepts combining technology, people, and processes to establish a more holistic context and approach for our study. The chapter concludes with the review of BIM and 4D BIM synergy with IPD and Lean construction (1.3), to emphasize the main concepts and issues which establish a theoretical basis for an analysis of collaboration and 4D use requirements, and for a proposal of 4D-based and Lean collaboration scenarios and prototype.



1.1 Digitalization and BIM/4D in AEC

1.1

1.2

1.3

The scope of our study includes concepts related to technology, processes and people interactions for multidisciplinary collaboration at the project meetings. Digitalization and adoption of BIM in AEC fostered many changes due to introduction of novel tools for digital design, such as BIM tools. The digital project models are not the only result of the new tools adoption, but the emergence of building information management concerning not only the building model but also the collaboration processes as well.

The aim of this section is to articulate the background of these various changes, emerging benefits, and issues to establish the basis of a general context of our research, and to further outline the 4D BIM as the focus of our study from the technological perspective. Therefore, first the section describes the evolution of practices and approaches towards Building Information Modeling/Management (1.1.1). Second, the section emphasizes various perspectives on definition and implementation of BIM from academia and from the industry (1.1.2). The section concludes, with an outline of schedule management and 4D BIM uses, emphasizes their benefits and further development requirements (1.1.3).

1.1.1 Evolution towards BIM

The following subsection aims to highlight the impact of the technological advancements on development of novel approaches to AEC project design and construction. First, we outline the evolution towards BIM emergence and development of novel practices (1.1.1.1). Second, we emphasize the key role of the need for information interoperability as an element fostering changes to the multidisciplinary collaboration, and impacting tools, protocols, project management methods.

1.1.1.1 Digitalization in AEC industry

Changes fostered by technology advancement

The last decades technological advancement brought changes to the established ways of proceeding in AEC and to the construction markets. Among various causes, the changes are encouraged by an expanding adoption of Building Information Modeling/Management (BIM) and novel digital tools. In particular, *a BIM project model becomes a technological core for sharing information and knowledge* (Eastman et al., 2011) (National Institute of Building Sciences, 2015). And it fosters a further digitalization of AEC approaches as well where the technological core is encompassed by exchanges, cooperation, and collaboration of project team members.

Also, *a holistic approach of digital project management* is one of the keys for an effective BIM-based project management (Jadhav, 2016). Over the project life cycle, the collective competencies are implemented into both the project design development and value engineering processes (Tory et al., 2008).

Lately, many construction leaders have focused on sophisticated technologies and materials to create projects with more innovative but challenging designs. A transformation of design process changes the professionals' workflow and habits, and questions the relevance of established methodology to a digital modernized toolkit. The early adopters and pioneers in digital architecture have prepared a *theoretical and practical basis* through their pilot projects and experiments (Oxman, 2008). Thus, they shift towards approaches that help with the challenging project goals through sharing skills, experience, and resources between the disciplines, and that become coherent with international standards and practices.

Digital tools and BIM implementation influences

AEC industry is changing under the influence of the latest information and communication technologies. The adoption of BIM and other digital tools naturally fosters the development of AEC, but it also creates a closer *bond between AEC and IT*. IT faces new challenges by working on solutions to answer the AEC need for more complex and innovative digital tools for project design and construction.

From a large-scale perspective AEC digitalization also adjusts to a shift towards the new digital globalized economy (Weippert and Kajewski, 2004). Together with the adoption of new tools, the established practices of design and construction, and management change and adapt as well. The adaptation subsequently provides a context for implementation of *new business models* (Schultz et al., 2013).

Also, the current tendency of the construction market is the increase of *demands for additional services* at the usual design and construction phases, and also for services related to facility management, operation, maintenance and even ownership, especially for newly built projects (Volk et

al., 2014; Dodge Data & Analytics, 2017). In addition, the broad implementation of BIM tools and innovative work processes create *a demand for the professionals with new skill sets*, thus it affects the education as well (Succar, 2013) (Pikas et al., 2013).

On a legal level, the BIM adoption initiate the creation of *new AEC state regulations and policies* for every construction market, thus it impacts the local legal and governmental contexts (Gu and London, 2010) (Smith, 2014). The research by Succar summarized these aspects as three fields of *a BIM framework, representing technology, process and policy fields* which facilitate the understanding and implementation requirements of BIM, and highlighting mutual dependences (Succar, 2009).

Yet, an AEC project stays dependent on a geographical location and related conditions, such as legislation or professional skills availability. Yet, some project requirements may influence the local context change as well. (Hillebrandt, 2000; EU BIM Task Group, 2017). The *local conditions directly influence the level of implementation* of the digital and BIM approaches. Also, for some projects, the value and relevance of BIM implementation are more convincing than for the others in terms of a local market context, requirements, location, and project type.

Emergence of Building information model

Since the first interactive computer aided design (CAD) system Sketchpad (Sutherland, 1963), an idea of new digital tools to reach beyond 2D drawings and 3D geometry models for AEC projects has been fostering the research.

During the 1970s, a number of ideas to add information and uses to a 3D virtual model have emerged through the works of professor Charles Eastman, who has described a visionary concept of *“Building Description Systems”* representing a general description system as a *“single database for communication, analyses, coordination, and fabrication”* (Eastman et al., 1975). His line of work continued with *“Integrated design databases”*, which sleeked to design new tools to organize project database systems and to support the project development process, it also represented *“a one medium”* to hold the project information and which was implemented with the developed *“Graphical Language for Interactive Design” language* (Eastman, 1979).

Further, Eastman also describes structure of a *“Computer Aided Engineering and Architectural Design System”* developed for design reviews, project modifications and analysis run with a single *“integrated building model”* (Eastman, 1980), with a use of digital project information not only for design purposes but also for decision-making and cost estimations.

In 1980s several first versions of design software solutions become available for purchase: CATIA by Dassault Systems in 1981, AutoCAD by Autodesk in 1982, Radar CH (future Archicad) for Apple Lisa Operating System in 1984, Allplan by Nemetschek in 1984.

In 1986, Robert Aish writes about a concept of *“Building Modeling”* (Aish, 1986) which provides a unique core to facilitate coordination and to assure design data consistency through an integrated CAD system. Such a system would be usable for all members of a multidisciplinary project team and would frame their workflow in a way to keep the model up to date. These ideas already stress the new topics of exploration about digitally-based collaboration and about the importance of the efficient project data updates relevant to our work.

Following the first two decades of research on integrated CAD, Björk describes a conceptual *“Building Product Model”* (Björk, 1989), which proposed to extend the use of the model not only for design, but also for construction and maintenance phases, and it would benefit from a RATAS

framework for an Object-oriented product model, which would be structured by information levels, classes and entities, and which would allow an AEC project team to access first the drawings, but also the project quantities and use instructions.

In 1992, Van Nederveen and Tolman introduce an approach to *“building information models”* (van Nederveen and Tolman, 1992), where a single kernel model is still the main source of project collaboration, yet they highlight a need for all project team members, such as designers, structural engineers and energy engineers, to have a domain-specific view on the building model. These inquiries and outlines also contribute to the exploration of appropriate to a specific purpose and user model views relevant to our work. The virtual reality tools as ArchiCAD 4 in 1991, and Rhinoceros 3D in 1992 also become available to the design professionals.

In the mid-90s, Eastman continues to work towards BIM and suggests that *“A building model is a representation of the building over all its life phases that is adequate for most (if not all) uses. This includes feasibility studies, all aspects of design and construction, and later, operation and facility management.”* (Eastman and Siabiris, 1995). The suggested definition sets a basis for a future understanding of BIM as a technological core for various project development phases. Eastman also presents a *“Generic Building Model”* (Eastman and Siabiris, 1995), which would be understood under a graphic and under a textual format. It was encompassing the virtual geometric primitives, architectural and structural elements, and the future uses of the spaces by the occupants. Eastman emphasized a need for other model views required for site planning or to support building systems.

The book *“Building Product Models: Computer Environments, Supporting Design and Construction”* by Eastman could be perceived as a milestone. Eastman emphasizes the previous decades of research and practice, and overviews evolution, tools, concepts, use-cases, and standards of building information modeling. He also emphasizes a need for the building information management (Eastman, 1999).

1.1.1.2 Interoperability needs with formats and new collaboration protocols

Exchange formats for building information data

Before the 1980s, the data exchanges on a project relied on proprietary solutions, but later the new open formats, like .dxf (Drawing Exchange Format), for the representation of drawings or geometry began to emerge to begin work towards interoperability between different construction domains software. The concept of *“Islands of Automation”* (Hannus., 1996) described the problem of missing links for data exchanges between architectural design, structural design and construction and a need for a common product model.

Project data is operated and stored in different file formats. Eastman summarizes some most common exchange formats between AEC applications as: *Image (raster), 2D Vector, 3D Surface and Shape, 3D Object Exchange, Game, GIS, XML* (Eastman et al., 2011). With BIM going beyond a digital representation of a project’s “visual” 3D model towards a semantic model, emerges a need for a file format for semantic data storage. Thus, 3D Object exchange formats enable information about 3D meshes, solids and parametric family’s storage, as well as a storage of information about colors, textures, attributes, objects and their relations, and rules.

Turk examines the modern issues of interoperability in construction from a systems perspective and through the *four levels of interoperability: technical, semantic, organizational and legal* (Turk, 2020). Each level has its own characteristics and presents the industry with different challenges. The evolution of BIM concepts and BIM implementation into practice have placed data into the heart of project design

development. Thus, an establishment of standards, protocols and data formats for project data management and exchanges was evolving in parallel with BIM, and it becomes essential for efficient project workflows.

According to Eastman's classification, the data exchanges between project design or management applications could be carried out through either *proprietary direct link or exchange formats*, or through *public (open) product data model exchange formats*, and through *XML based exchange formats* (Eastman et al., 2011). Today, BIM model exchanges and interoperability would be either based on BIM software proprietary file formats and follow the *closed BIM processes, or on open BIM* vendor neutral processes using the Industry Foundation Classes (IFC) and Extensible Markup Language (XML) open file formats.

Evolution of open file formats

Laakso and Kiviniemi (Laakso and Kiviniemi, 2012) review the history of IFC standard development, and trace that *IFC emerges in early era of building information* use in mid 90s, even before the establishment of BIM term and approach, but it anticipated shift from 3D surface and shape CAD to semantic 3D object-based BIM.

From more technical point of view, and despite the quite collective understanding by some end-users of IFC as mainly a file format for exchanges, it is also data model (schema) and an open standard that ensures interoperability. Laakso and Kiviniemi define IFC as: *"...an open, formal, international, consortium standard currently involved in a hybrid standardization process designed to enable indirect horizontal compatibility between AEC/FM software applications"* (Laakso and Kiviniemi, 2012). And today it is a part of ISO 16739-1:2018 "Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries" (International Organization for Standardization, 2018). The structure of the data schema includes conceptual layers: resource, core, interoperability, domain, which provide necessary elements for data input, sharing an interpretation.

In 1994, STEP became an international standard: ISO10303:1994, Industrial Automation Systems and Integration - Product data representation and exchange. And the same year Industry Alliance for Interoperability (IAI, future International Alliance for Interoperability and Building SMART) began to work on IFC 1.0 to create a set of consistent data representations for building information using recourses from previously developed ISO STEP standard and EXPRESS modeling language (Eastman et al., 2011). IFC 1.5.1 was the first to be supported by a commercial software in 1998 (BuildingSMART, n.d.). Further, IFC 2.0 release in 1999 was also supported by some commercial software products. Next, IFC 2X in 2000, ifcXML and IFC 2x2 in 2003 were already developed under ISO PAS. Following the wider use of BIM in the industry, IFC 2x3 release in 2006 represents many useful additions as *"the useful minimum"* (Laakso and Kiviniemi, 2012), and establishes a real useful model for interoperability.

In parallel, the efforts to standardize encompass not only on the format level, but also the technical and organizational aspects of exchanges. Since 2006 the IFC Model View Definition Format (MVD) specifies the data exchanges between different application types and presents an answer to technological aspects of data exchange. Following the development of MVD, since 2007, the methodology of Information Delivery Manuals (IDM) as a part of efforts for standardization represents a process which *"...provides a universal, repeatable, and verifiable methodology for creating information exchanges by industry professionals."* (Karlshøj et al., 2012). It includes process maps, exchange requirements, functional parts, and concepts, and it answers not only technological challenges of the exchanges but includes the domain specific workflows for an AEC project team.

Together with the open formats of *IFC and MVD, since 2011, BIM Collaboration Format (BCF)* as an XML based format, reinforces exchanges between different software and assists with issues reports during coordination. Finally, arriving in 2012, IFC 4 extends the list of its predecessors' features. Such an approach to standardization supports integrated construction process (Laakso and Kiviniemi, 2012b).

Tendencies of data exchanges

Thus, till today, there were several decades of work towards data exchange standardization and open format development. Yet, the weak market demand for the exchange standardization did not aid to foster such development or the adoption of collaborative model-based construction processes (Laakso and Kiviniemi, 2012), nor the standards development supported on government or industry advancements have not yet surpassed the isolation of “automation islands” for the most effective collaborative use of BIM (Sacks et al., 2016). *Miettinen and Paavola (2014) also observe the simultaneous and inter-influential development of BIM technological solutions and of the BIM standards, and speculate that multiple solutions will persist, despite a tendency toward the unification of practices* (Miettinen and Paavola, 2014). *Even with the software and standards continuous improvement, there is still a need for better interoperability and data-checking capability* (Lee et al., 2015).

Pauwels et al. present an overview on the use of semantic web technologies, such as *Resource Description Framework (RDF) and Web Ontology Language (OWL), and of linked data* technologies in AEC (Pauwels et al., 2017), and they perceive an increase of use of such technologies since the 2000s. The IFC approach structures the data, but OWL gives tools to implement better interoperability and reasoning (Boje, Guerriero, et al., 2020). The use of Semantic Web aims *to improve exchanges, to create a stronger connection among different data sets from the different project domains, and to apply logical rules and proofs to the data* (Pauwels et al., 2017). These aspects reinforce value and flexibility of BIM and enable web-based data queries, which are valuable for more efficient collaboration and decision-making on the project.

The recent work of Building Smart towards IFC 5 aims to modernize the IFC data structure for object-based exchanges in a transactional environment and to the new use-cases (Berlo et al., 2020). The work also seeks to adapt the IFC structure to the emerging frameworks and to the existing technologies for semantic data and web exchanges (Berlo et al., 2020). Such a change of an approach to data structuring would make the format more adaptable, therefore, it would speed up adaptation to future requirements, as well as include the nD data and Digital twins' data.

An overview of the studies concerning BIM subjects shows a significant increase of interest in research topics focused on Digital twin since 2018 (Boje, Guerriero, et al., 2020). The latest shift of Project Life cycle Management from “Human-centric” towards “Things” or even “Everything centric” enforced by the technology drives *evolution from BIM platforms and social collaboration towards IoT and more open platforms* (Turk, 2020). The data exchanges formats and protocols follow these tendencies.

Thus, there is a need to make a *transition from information-based interoperability towards knowledge-based interoperability*, and a need to follow the evolution towards construction 4.0 (Turk, 2020). There is also a need to design, build, and operate *more integrated and more dynamic environments* and to improve automation and information cohesion (Turk, 2020) (Boje, Guerriero, et al., 2020).

Key points of 1.1.1

Evolution towards BIM

- We described the emergence of ideas on Building Product Modeling and Building Information Modeling, and some key points of the development of digital tools and concepts for AEC. Also, it illustrates a path towards the identification of a need of more comprehensive approaches to project design and of modernization of collaboration and data exchanges.
- The search for efficient data exchange methods endures as one of the important subjects for decades to answer the need for interoperability, easy exchanges, gathering all information types and automation. The established exchange formats and standards have presented AEC professionals with the necessary tools to design and review projects, yet they are constantly adapting to the new demands, technologies, and collaboration processes.

1.1.2 BIM emergence and implementation outline

The following subsection aims to establish an understanding of BIM through an outline of the term and of the related concepts (1.1.2.1), and of their establishment into research and practice (1.1.2.2). It also aims to emphasize that BIM implementation brings various benefits as well as challenges to various aspects of project design and construction, including to multidisciplinary collaboration and a need for more efficient tools, processes and protocols (1.1.2.3).

1.1.2.1 Evolution of BIM

BIM term and phenomenon

While BIM has already established its place in research and industry, it may be perceived as “a multidimensional, historically evolving, complex phenomenon” (Miettinen and Paavola, 2014), or as a “subject to variation and confusion” (Eastman et al., 2011). Thus, it may be useful to provide a more detailed definition or interpretation of the term, which would describe its complexity through an overview of BIM definitions in literature, and to outline its understanding applied to our research.

In the most core and basic understanding “BIM” as a Building Information Model “... is a three-dimensional geometric model that is data rich” (Kensek, 2014). Within this understanding, the model is the technological core of the project; that, on a social level, impacts the collaboration within the design team of a construction project. Yet, in addition to the model itself, BIM: “... is a methodology to manage the essential building design and project data in digital format throughout the building’s life cycle.” (Penttilä, 2006); or “...IT enabled approach that involves applying and maintaining an integral digital representation of all building information for different phases of the project life cycle in the form of a data repository.” (Gu and London, 2010). These definitions include **not only the model data, but also the methods and approaches** to the work on a project throughout its life cycle.

Furthermore, to encompass all the elements, the acronym refers not only to the model but to Building Information **Modeling/Management as an activity and a process** (Eastman et al., 2008), which is crucial to effective project development and quality results. Moreover, BIM process is “... a collaborative process covering business drivers, design, construction and maintenance processes, and it provides open information standards for all parties involved in the project” (Ghaffarianhoseini et al., 2017). This understanding of the term is especially important for our work, since it highlights the **collaborative nature of the process**, and it follows an argument that BIM brings a shift “toward an integrated and interoperable work flow” together with “a paradigm shift from drawing to modeling” (Eastman et al., 2011). This provides a connecting bridge between the understanding as a model and a wider approach encompassing project information management.

Also, BIM as a set of technological tools and organizational solutions not only provides an accurate complex project information description but also aims to be the instrument that is “...expected to increase interorganizational and disciplinary collaboration in the construction industry and to improve the productivity and quality of the design, construction, and maintenance of buildings.” (Miettinen and Paavola, 2014). According to a recent understanding of the term’s meaning, which, in addition to modeling and collaboration, comprises a **way to improve productivity**, BIM: “... is one of the key technologies and digital platforms to improve the construction productivity and collaboration...” (Jin et al., 2019), or in a more brief and broad way: “Building Information Modeling ... is a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a facility in virtual space.” (The BIM Dictionary, 2021).

The definitions provided by academia continue to evolve as the acronym's scope expands. Beyond modeling and management, on a larger scale BIM is a *technological and procedural AEC change of paradigm*, and it may be seen as *a set of interacting policies, processes and technologies* (Succar, 2009). To mention several definitions from the policies, the USA standard vision of BIM is that it provides: *“an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format usable throughout its life cycle by all.”* (NIBS, 2007). Otherwise, the more recent ISO entry defines Building Information Model through a *“... use of a shared digital representation of a built asset ... to facilitate design, construction and operation processes to form a reliable basis for decisions”* or more encompassing *“expression of digital innovation”* (ISO, 2018a).

BIM uses

Nowadays, many of the AEC professionals develop their projects with the help of digital tools and practices and, this way, find themselves able to design, manage and build not only regular projects but also more challenging and ***complex architectural expressions*** (Penttilä, 2006). Yet, not all of them have fully integrated the use of 3D semantic enriched models into their work, and those are fundamental for the BIM project design and management methods (Oxman, 2008) (Delcambre, 2014). To assist with the progressive adoption and implementation of BIM, much research, organizations, and government agencies work on the establishment of standards, development of implementation protocols and guidelines. The standards and guides provide AEC professionals with organization methods and with implementation examples (Sacks et al., 2016), and outline further potential BIM uses as well.

Naturally, BIM uses are conditioned by the project context, strategy, team, and other conditions, and even though there are resources assisting with BIM workflows and standardization, the “custom” nature of every project would still require some adjustments. For example, the work on guidelines by Kreider and Messner proposes a classification system to assist with the BIM implementation, and identifies BIM use as: *“... a method of applying Building Information Modeling during a facility's life cycle to achieve one or more specific objectives”* (Kreider and Messner, 2013); such use has the following purposes: *to gather, generate, analyze, communicate, realize*; these may be put in parallel with decision-making of various types. In addition, any BIM use also has characteristics: *facility element, facility face, discipline, level of development* (Kreider and Messner, 2013).

In the same line of work Messner *et al.* summarize BIM (model) uses in “BIM Project Execution Planning Guide” in order to assist with identification and prioritization of the most appropriate and beneficial uses to a particular project (Messner et al., 2021). Among others the guide lists following common model uses:

- *analyze program requirements,*
- *author, coordinate and review design model and 4D model,*
- *capture existing conditions,*
- *manage construction site logistics, layout construction work,*
- *author cost estimate (Messner et al., 2021).*

Regarding project development phases, ***4D model authoring is suggested at early design phases.***

BIM levels

On a project model level, a BIM model contains various pieces of information about the project and becomes more detailed throughout project development phases; the term of Level of Detail (LOD) emerges to manage these details.

For example, in a BIM project protocol developed by the American Institute of Architects (AIA) in 2013 and recently updated by the BIM forum in 2019 *proposes LODs 100-500*, which correspond to the project life cycle phases. In detail, a BIM model with LOD 100 is would contain “model elements or symbols showing the existence of a component but not its shape, size, or precise location”, thus it is *concept representation*; the next LOD 200 uses “a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation” to define an element, and is also *approximate representation*, suitable for design development; further LOD 300 and 350 already defines specifics (quantity, size, shape, location, orientation, coordination link etc.), and is a precise representation of late design phases; the LOD 400 continues with detailing adding “fabrication, assembly, and installation information, and the BIM model is therefore very detailed, suitable for installation and fabrication purposes; finally LOD 500 “relates to field verification” of an as-built project (BIMForum, 2020). These levels present one approach to a system for hierarchization of model element details.

Another example is the guidance form PAS 1192-2 proposes outlines levels of project information model details as:

- *brief,*
- *concept definition,*
- *design,*
- *build and commission,*
- *handover and close-out,*
- *operation and in use.*

Naturally these are also aligned with decision-making points for the client (BSI Standards Publication, 2013). In the French construction context, the organization inspired by LODs proposes “levels of development”⁶ (ND1-ND5) which represent an expected level of information in a BIM model according to specific project phases required by legislation; where ND3 introduces design team collaboration and ND4 modeling of elements for the works to be executed (Syntec-Ingénierie, 2011). Hoyet, Duchène and Fouquet outline a more detailed connection of BIM information details to French legislation requirements, and suggest *4D BIM use corresponds to ND4 and construction phase, and also suggest that a 4D model may be seen as a critical pass model* (Hoyet et al., 2016).

While the concept of detail level of development concerns the model, on a project information management BIM level the concepts of *“BIM maturity levels” increase progressively from CAD to iBIM* inside an organization (BIS (Department for Business Innovation & Skills), 2011); or with “BIM Capability Stages” inside an organization or in regards their relation with other organizations (Succar et al., 2012) illustrate that BIM implementation also progresses on technologies, process and policies levels from a basic object-based modeling (Level 1), to a more complex model-based collaboration (Level 2), and finally to an integrated network-based collaboration (Level 3). *The 4D occurs usually on BIM Level 2 or during model-based collaboration.*

1.1.2.2 BIM adoption and research

BIM adoption by AEC professionals

Every innovation and change adoption passes through innovation diffusion stages as awareness, persuasion, decision, implementation, confirmation, according to “*Diffusion of Innovations theory*” proposed by Rogers (Rogers, 2003), the levels represent progressive ***communication of innovation in a social system***. This theory has been used by Kassem (Kassem and Succar, 2017) (Ahmed and Kassem, 2018), Gledson (Gledson and Greenwood, 2017) and Hochscheid (Hochscheid and Halin, 2018) to describe, structure and understand BIM adoption in AEC. Hochscheid and Halin (Hochscheid and Halin, 2020) propose to distinguish 5 stages to BIM innovation adoption:

- *awareness,*
- *intention,*
- *decision to adopt,*
- *implementation,*
- *confirmation.*

The confirmation stage is followed by innovation diffusion. These stages offer a more detailed view of BIM adoption process when applied to a single firm or in regards of BIM adoption rates in the industry. They also outline tools for a more precise understanding of BIM adoption. Yet, in the most studies published previously the terms adoption and diffusion, as well as implementation sometimes refer to the same idea of adoption in general.

The importance of understanding the adoption drivers and processes by project stakeholders and policymakers on levels inside the organization and market wide was supported by a study on BIM adoption taxonomy. It reported that the most influential factors to a decision to adopt BIM would be:

- *communication and behavior,*
- *organization size,*
- *relative advantage,*
- *compatibility,*
- *cohesive pressures,*
- *organizational readiness,*
- *top management support (Ahmed and Kassem, 2018).*

Construction and infrastructure projects have been advancing in implementation of BIM, with approximate use in half of projects in the USA, the UK, France, and Germany (Dodge Data & Analytics, 2017). According to an AEC market reporting McGraw Hill, the percentage of contractors with high BIM implementation levels intensively grows and varies from 40% to 80% for the major markets (Japan, New Zealand, South Korea, Canada, the UK, France, Australia, Germany, Brazil, and the USA) (McGraw Hill Construction, 2014).

In addition to market reports, the studies from academia investigating BIM adoption and measuring BIM maturity has covered 21 countries and analyzed the current situation with ***a maturity matrix***, which indicates that none of the countries has achieved a high level of maturity (Succar, 2010; Kassem and Succar, 2017). Various levels of granularity may be applied for such analysis; however, ***objectives, benchmarks, skills, and technology infrastructure*** (software, hardware, and networks) are important components of the BIM adoption system. Some studies consider the USA and Scandinavian countries to be the current leaders in BIM implementation and practices, and also show the highest ease of integration in Singapore and Norway due to the governance policy and economic influence factors

(Smith, 2014). Others consider UK to be a current leader from the maturity matrix perspective (Succar, 2010; Kassem and Succar, 2017).

Following the overview of global scale, it is important to outline BIM adoption in *France and Luxembourg* due to our research connection to these professional contexts. According to the European Commission report on the French AEC industry, even if the efforts on BIM implementation are relevant to the current state, only a little more than **10% of firms have declared using BIM regularly** (Eurostat, 2017). For about a half of firms, the main **concerns of future implementation are the cost and complexity of BIM**.

A more specific study focused on BIM adoption and implementation in *French architecture firms* reveals that **10% of the respondent firms consider themselves to use BIM level 2ⁱⁱ** and provide a positive feedback on the use, also 28% of firms use BIM level 1ⁱⁱⁱ and they rather feel concerns about the complexity of the use, finally the rest of the respondents operate at BIM level 0 (Hochscheid, 2021). Thus, we could say that to many the implementation is rather in progress. Many industry actors await for a further development of national policies on the macro level (Hochscheid and Halin, 2018).

In 2014 the IT barometer survey investigation in *Luxembourg* revealed that most AEC firms were not familiar with BIM, with the highest **awareness among architects** (about 40%) (Kubicki and Boton, 2014). Thus, architecture professionals are likely to adopt **the role of innovators for industry changes**. The AEC professionals have developed a BIM application guide (CRTI-B, 2018) and other assistance documents⁷. Such strong industry and research initiative found a support at the governmental level since Luxembourg has developed a national BIM strategy (Eurostat, 2018).

The cited studies were conducted some time ago, and the survey's results did not seek to portray the current state of the industry, but to outline the tendencies and emphasize the context. Additional studies would be necessary to acquire more recent data.

BIM, 4D and collaboration topics in research

"BIM" has become one of the major keywords for AEC industry and research. Santos, Costa and Grillo reported after a quantitative bibliometric analysis of research items (2005-2015) that: **2010 represents growing point and increase of research productivity** on the subject, they suggested as well that BIM research is reaching advanced levels of maturity (Santos et al., 2017). A semantic analysis by Yalcinkaya and Singh of the main interest topics in BIM research presents following items:

- *implementation and adoption,*
- *energy performance and simulation,*
- *academy and industry training,*
- *information exchange and interoperability,*
- *safety management,*
- *urban/building space design and analysis,*
- *construction and project management,*
- *design codes and codes compliance,*
- *as it is, as-built data,*
- *promotion and technology development,*
- *maintaining and managing facilities,*
- *architectural design process (Yalcinkaya and Singh, 2015).*

ⁱⁱ BIM collaboration between different project teams

ⁱⁱⁱ BIM and CAD use for project development by the project teams separately

The proposed semantic analysis outlines most of the topics, regarding which our research may be investigating in the topics of technology development, design and construction processes management.

Further, according to a global taxonomic review of BIM studies 2006-2017 by Saka and Chan the highest number of *cited BIM publications from North America, followed by Europe*, and considered by the authors to be the leading continent was in BIM adoption, yet the highest number of BIM publications was from Asia, which could be due to the increase of BIM awareness in China, Malaysia, Singapore, and India (Saka and Chan, 2019). An analysis of research items from Scopus database reports a knowledge gap in African countries in terms of research on AEC digitalization (Aghimien et al., 2019). Even though, many studies investigate and compare BIM research context, many aspects influence the study's results, such as perspective, methodology, scope, etc., thus any conclusions should be drawn with the aspects considered.

Regarding the 4D topic in particular, Santos, Costa and Grillo identified *BIM-based tools and Schedule Management* among other trends with potential for development, and highlights that BIM-based tools will continuously seek for more automation of all processes (Santos et al., 2017). Also, a systematic review of keywords in scientific publications on BIM from 2007 to 2016 by Lemaire et al. presents a co-occurrence network. Where *"BIM"*, *"Building Information Model/Modeling"*, *"IFC"* and *"Interoperability"* presented to be top ranked research keywords, *"Collaboration"* (ranked 6th) and *"IPD"* (ranked 19th) (Lemaire et al., 2019).

The review also identified seven major distinguished research clusters (communities): *BIM (the core and global scales)*; *Industry Foundation Classes*; *Information Technology, Facility management*; *Collaboration*; *Computer aided design, Building* (Lemaire et al., 2019). The review displays the *"4D CAD"*, *"4D BIM" as a meaningful nodes of Collaboration* research community, together with *"3D models"*, *"communication"*, *"visualization"*. In addition, on global cluster scale the *Building community also has the "4D" node, as well as "construction planning"*, *"5D"* which are connected to *"modeling"* (Lemaire et al., 2019).

In addition, an analysis of BIM-based research by (Jin et al., 2019) revealed a strong connection among the Keywords *"visualization"*, *"construction safety"*, *"scheduling"*, *"4D"* and *"construction planning"* within the same research cluster. Also, it observes that *"lean construction"*, *"4D BIM"*, *"interoperability"*, *"ontology"*, *"planning"* as keywords are gaining momentum together with directions of research on: *synergy between BIM and IPD*; *integration of BIM with other digital technologies*; *development of prototypes enhancing lean construction, BIM and sustainable practice* (Jin et al., 2019).

The existing research proposals on construction monitoring investigates the use of IoT and data analysis for automation. For example, the work of Soman, Raphael and Varghese investigate a possibility to *improve automated monitoring of construction through the automated data collection* through wireless sensor network facilitating identification of construction activities with aid of structural responses. The data may be used not only to monitor construction progress and productivity, but also offer automation opportunities (Soman et al., 2017).

The project data issued from BIM models, simulations, documentation and sensors presents comprehensive sources for more informed decision-making, yet the increasing amounts of data and complexity also *present challenges to its efficient management and use*, highlighting needs for implementation of *automated assistance and artificial intelligence* (Nikolić and Whyte, 2021).

In addition, regarding the related fields, the latest bibliometric analysis extended from research on BIM to its' synergy with GIS and Web environments identified an exponential growth of research in the areas since 2015, and also identified *a gap in the research area of and Web interoperability solutions* among others (Shkundalov and Vilutienė, 2021). They point out that semantic web solutions (BIM+GIS) would be of a *support for monitoring supply chain* management (Shkundalov and Vilutienė, 2021), which also highlights the interest to surpass the dimensions of BIM and progress towards more practical implementations of digital continuity and connection of virtual model to the real construction. Another analysis investigated the connection between BIM and energy simulation reports *lack of established and efficient workflows* to assure interoperability between BIM and Building Energy Performance Simulation beyond the envelope simulations but also the systems simulation and not only at design phase but also for operations (Andriamamonjy et al., 2019).

Since the establishment of the idea of BIM, the research community had an opportunity to investigate many areas of application, expand to further concepts like 4D and nD BIM, extend to related fields of project management or robotics, search for automation, efficiency, and innovative uses.

1.1.2.3 BIM Benefits and challenges

Improved design, collaboration, and efficiency

Various studies discuss the topic of benefits and challenges of BIM implementation, and reports on the implementation from real projects add valuable feedback and support the discussion. Among the topics there are technological aspects, data and knowledge management, collaboration and standardization, project management and decision support, design and simulations, economic and legal aspects, etc. One of the first examples of BIM benefits may be illustrated with the MacLeamy curve which shows that the increase of an effort during design phases is aligned with the improvements of the project costs and error control.

BIM approach adds supplementary model components and annotations to the geometry visualization (Mazza, 2009). Penttilä sees the use of technology and digital tools benefit in *improvement of design creativity* and in achievement of *better driven projects* (Penttilä, 2006). However, BIM implementation opinion or experience is *seen in different ways by different project stakeholders* (Becerik-Gerber and Rice, 2010; Vass, 2017). Project stakeholders' perception often depends on how well they are informed on the subject and on their experience. Investigation on BIM implementation is important since each critical and realist description of the experiences provides a better understanding and contributes to more efficient use (Fox, 2014). Nevertheless, the majority of accurate feedback on *BIM use in real projects comes from the firms with a high-level BIM implementation*.

BIM use and implementation feedback from a firm that has not conducted a BIM project is somewhat different from a firm that has already accomplished a pilot BIM project or even delivered several projects. The feedback on the *real projects implementation* of contributes to further development of the *applied uses*, and the feedback on *percepted utility of BIM* by those who had not yet implemented it addresses a *better understanding of adoption or rejection factors*.

During the last two decades, various surveys and barometers investigated the diffusion and use of CAD and BIM, such as: Smart Building reports, Scandinavian market studies, Eurostat reports, Digital Transition Plan in the Building Industry⁸, and Information Technology (IT) barometer surveys. Research surveys and studies with industry professionals on BIM diffusion, adoption and implementation often report the high interest in *BIM reinforced a more cohesive multidisciplinary collaboration*, or they report a *belief that project quality improvements* may be achieved with BIM.

According to the McGraw Hill Construction report, *collaboration improvement is the second most expected BIM benefit* after the reduced errors and omissions (McGraw Hill Construction, 2014), for example in a study by KPMG more than 80% of respondents *expect an increase in collaboration quality* of an owner and a contractor (KPMG, 2015). These aspects indicate the value of stronger and closer collaboration and professionals' attention to their BIM-based workflow organization.

Need for relevant skills and protocols

Also the market report by McGraw Hill reveals that among project stakeholders and their benefits from BIM contractors generally reach a positive return on investment more quickly than design professionals (McGraw Hill Construction, 2014), and that they may become leaders in fostering the competence development of other stakeholders. Moreover, *BIM competence* slowly becomes an important *criterion for choosing project team members*. The adoption of BIM by AEC industry professionals fosters the *implementation of new knowledge, work protocols and tools into project development practices* (Weippert and Kajewski, 2004). The projects developed with the innovative digital practices of 3D modeling benefit from the *improved communication, coordination, and production* on a project due to the possibility of access to building information model and interactions with it (Succar, 2013). In addition to surveys, some case studies report that BIM use *improves communication not only during design but also during construction* (Machado et al., 2020). BIM brings benefits to project design and construction projects, and extends to facility management, demolition and infrastructure projects.

The French digital initiative has conducted a survey report on identifying the perception of BIM use by French AEC industry professionals. According to the survey, there are three main advantages to the use of BIM. The first advantage is stakeholders' *encouragement for more cohesive collaboration and exchanges* on a project. The second perceived advantage of BIM use is a *decrease of the amount of design errors*, and the last is the improvement of *project quality* (PTNB, 2017). Yet, the survey identified three main perceived disadvantages of BIM: *lack of internal skills* (suggested by more than 45% of participants), *software costs* (suggested by more than 40% of respondents), and *lack of standardization* (suggested by more than 35% of respondents) (PTNB, 2017). These *concerns are mostly related to the technological core and professional practices*.

An establishment and implementation of the guidelines by AEC organizations stays essential for enabling a possible of benefit from BIM processes and technologies (Sacks et al., 2016). A study by Ghaffarianhoseini *et al* lists the lack of demand to use BIM from the clients, *need for investment in software, hardware and training, development of internal collaborative BIM procedures* as reasons to not adopt BIM, as well as difficulty of adoption itself for some practices defined by non-user-friendly software or lack of interoperability, skills or experience (Ghaffarianhoseini et al., 2017). The study also concludes there is a *need to comprehensively quantify the benefits of BIM beyond the case studies and to summarize evidence* of BIM effectiveness (Ghaffarianhoseini et al., 2017).

The change in policies and standards, emergence of sophisticated digital tools, change of work practices and client demands bring new perspectives on design and on construction. From the economic point of view the changes shape a project as a more attractive investment opportunity. From the collaboration organization point of view, they outline a *need for a stronger communication on the project and bring new roles and relationships to the project* (Singh et al., 2011), as well as novel opportunities for integrated project delivery and lean approaches.

Key points of 1.1.2

BIM emergence and implementation outline

- Since the beginning BIM has grown into an established, yet a dynamically expanding approach to project design and management that draws benefits from project team collaboration and from various project information types.
- The presented BIM context within the more global digitalization in AEC Industry context portray is important to understand better their features and issues common with 4D BIM and their impacts on collaboration, which are the subjects of our research.

1.1.3 4D BIM and schedule management

The presented digitalization and BIM evolution in AEC establish a comprehensive technology and processes context of our study. However, the focus for us is on 4D BIM and its collaborative use. 4D BIM shares features of 3D modeling, of schedule management and of multidisciplinary collaborative design and decision-making of BIM. Therefore, the following subsection aims to overview and outline the 4D BIM and scheduling related concepts, such as construction project schedule management approaches and the 4D concept (1.1.3.1). Further, it overviews 4D BIM adoption and uses (1.1.3.1), as well as 4D BIM benefits and challenges (1.1.3.2). Finally, it emphasizes need for more innovative technologies, processes, and skills (1.1.3.2).

1.1.3.1 Project schedule management and 4D BIM concepts

Program, planning and schedule

As much as design is a vital part of a project, the project timeline establishment and construction schedule are essential for any AEC project management in general (design, construction, manufacturing, etc.) and for construction management. A construction project management usually has some essential ideas for the future timeline management (like an estimated duration or a delivery timeframe) since project's beginning and before the design development starts. Further, together with the development of project's design the time management evolves from a simple *programming*, to a *planning* and then to a *detailed scheduling* (CIOB, 2018), like a BIM model's increase of level of detail (LOD). Thus, *program*, *planning* and *schedule* are the tools for project time management. The time (schedule) management basic concepts are formalized in advance to the project to start with relevant resources and cost and liability management.

At an early point of development every project has an established *program*, with some aspects estimated regarding timeline and cost basis. Next, these project aspects advance to a *planning*, which is created by a group of AEC professionals with the timeline estimations based on their experience (CIOB, 2018). The planning output provides documented decisions on project organization and construction preparation. Further, the planning is used as a basis for more detailed management of project time as the *schedule*, which is reinforced with calculations, plans, resources, and risks enouncement (CIOB, 2018). Finally, a *dynamic schedule* is used during the pre-construction and construction phases (Figure 4).

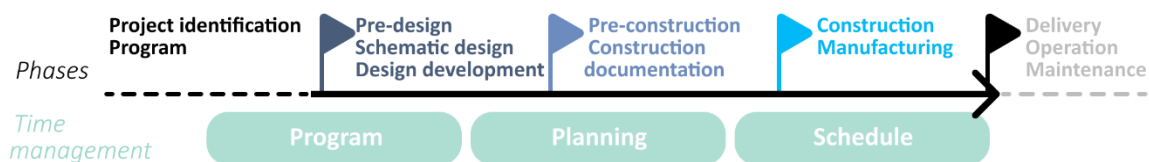


Figure 4 Schema of Project development phases and time management sequence

The adaptive and dynamic time management may combine some elements of all time management approaches to adapt them to each section of the project (CIOB, 2018). Usually, the program and early planning start at the same time with the early design concepts, the basic information about project timeline estimations emerges when the project's shape (early design) is defined. An efficient dynamic schedule assures review, revision, monitoring, updates, and impacts.

The precise titles (naming) and types of design and construction project phases depend on the project context. Therefore, *various phases of advancement hold different names* and have assignments based on the local legislation and policies, project type, and contract type. Despite requirements towards these phases naming specific to every country, at a large scale, the project starts with the planning, passes through design and construction, ends with delivery, or includes maintenance interventions. Also, for certain projects a facility management phase is included as a part of project development contract. Most of the project-related risks should be designed during the planning and design phases and managed during the construction phase (Zou et al., 2017).

Schedule management approaches summary

Bourne and Weaver outline the *origins of project schedule management from the first methods*: of a bar chart (1910s) to a Gantt chart (1920s) use to measure the difference between planned and actual activities of production; enhanced by the ideas of milestone and flow line charts (1930s); in further decades followed by an emergence of project management and of operation research which proposed a critical path method (CPM) (Fondahl, 1962), and program evaluation and review technique (PERT) (Pohl and Chapman, 1987) (Bourne and Weaver, 2018). Therefore, these methods have more than a century long history of development and implementation in AEC practice.

However, time management can be approached with different methods, such as fairly common CPM and PERT, which have been used for numerous decades but do *not show the highest efficiency according to the arguments comparing to more recently emerged methods* due to the lack of resources taken into account or prediction inaccuracies, or other aspects accounted for by linear projects (linear scheduling method (LSM), and line of balance (LOB) (Russell and Wong, 1993) (Tapia and Gransberg, 2020); and emerging approaches (Last Planner® System (LPS®) (Darwiche et al., 1988), critical chain method (CCM), virtual construction (VC) (Boton, 2013).

A study by Boton emphasizes upon some of these methods and outlines that there are *traditional methods* as CPM and PERT, *linear methods* as LSM and LOB, and *new methods* such as LPS®, CCM and VC (Boton, 2013). For instance, the emphasis outlines that CPM is by far one of the most used methods for project schedule management, and it mostly relies on Gantt charts, it clearly highlights the critical path activities, estimates the necessary time, but not all information types about necessary resources are available within CPM. The PERT method is focused on the probability of attending the goal, and it takes in account numerous scenarios, while highlighting the critical path as well. Yet, the resources are not in the primary scope of the method. The linear methods do not bring into scope resources either but offer visualization of linear sequence of construction activities or highlight their location. However, the methods referred to as “new methods” according to the analysis of Boton seek to integrate and to apply lean principles, constraint theory and advanced virtual modeling methods to construction management.

Another study by, Garcia-Lopez and Fischer also proposes a review of construction activities management methods and their limitations. They also propose 3 types of the management methods:

- *deterministic construction models (like CPM, Artificial Intelligence guided planning (Darwiche et al., 1988), Tri-Constraint Method (TCM) (Morkos, 2014) assist with planning and representation but do not assist with construction activities tracking;*
- *stochastic risk models (like PERT, Bayesian Networks (BBN) (Liu, 2010), Risk Network Analysis (Dawood, 1998)) assist with activity precedence constraints, considers variability and occurrence impacts on the project duration, but they do not integrate project control as well;*

- **stochastic simulation models** (like *Work Flow Variability* (Tommelein et al., 1999), *Multiobjective analytic model (MAM)* (González et al., 2009), *Trade and Project Workflow models (TWM, PWM)* (Brodetskaia et al., 2011)) assist with simulation of flows, variability, connect activities, yet the models rely on time studies or statistical inference (Garcia-Lopez and Fischer, 2018).

Hence, Garcia-lopez and Fischer outline that to support a representation of construction flows and progress managers may implement **models based on project progress** that quantify variation at the activity and flow levels, like LPS®, Location-based Management System (LBMS) (Kenley and Seppanen, 2009), Construction Flow Index (CFI) (Sacks, Seppänen, et al., 2017) or Activity-Flow Model (AFM) capable of tracking construction activities, flows, and their interactions to assist filed managers with tracking of project progress (Garcia-lopez and Fischer, 2018). Figure 5 presents a summary of introduction of the abovementioned methods and approaches on an approximate timeline.

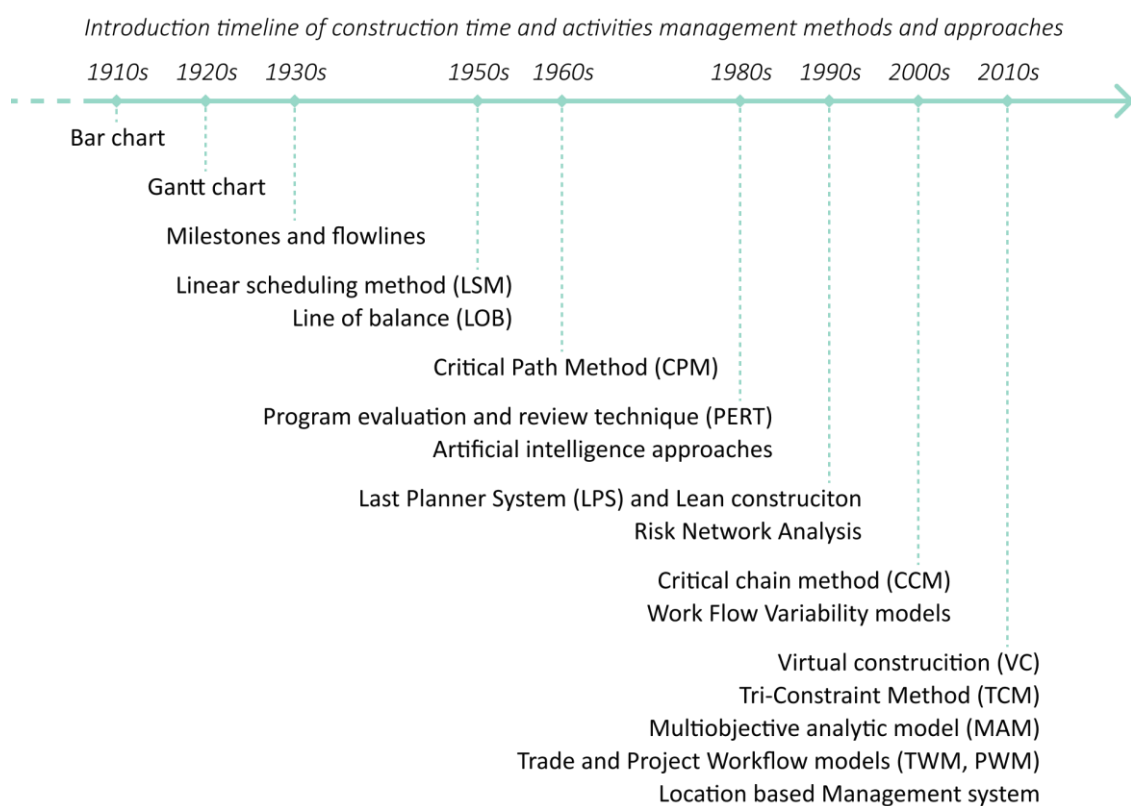


Figure 5 Schema of Introduction timeline of Construction time and activities management methods and approaches

There is a number of approaches assisting with scheduling and construction management, yet with the increasing projects design complexity the new knowledge-based methods would assist with decision-making during project planning (Hajdu and Isaac, 2016). For example, CPM is widely used to forecast project completion, yet it is not created by the teams executing the construction tasks, and it does not fully considers the constraints thus works on assumptions, like it *“fails to consider the impact of coordination and reciprocal work in the design phase and it inadequately considers time-space conflicts during construction and the impact of those conflicts on production activities.”* (Fischer et al., 2017; Ch.10). In addition, CPM does not assist with analysis of causes of delay (Tapia and Gransberg, 2020).

Sacks, Korb, et al. compare the concepts of “traditional” and Lean planning, and outline certain limitations of CPM such as:

- *focus on activity duration and not on production details,*
- *relationship between activities describing precedence is clear, yet accompanying activities or fuzzy dependences are not considered,*
- *the fluctuations in production are not considered (Sacks, Korb, et al., 2017).*

Furthermore, Gantt charts are comparable to a “black box”, providing the time management-related information, but not indicating enough details about on site location or construction team (Sacks, Korb, et al., 2017). However, in a location-based planning there is a possibility to model every activity and every location, in addition they may be considered a separate “product” (Sacks, Korb, et al., 2017), therefore planning and control encompass more information for efficient and value focused decision-making.

The Integrated project delivery (IPD) approach presents *planning as a collective activity* which is supported by “... every intellectual action that must be accomplished to enable physical realization of the project.” (Fischer et al., 2017; Ch.14), but the recurrent Gantt chart and CPM methods do not provide visualization of time and space conflicts which would be efficient and clear for the entire project team (Fischer et al., 2017; Ch.12).

In addition, IPD also suggests that to optimize efficiency and usability there *is a need to combine different scheduling tools and* is one of the tasks of an integrated information system which would help the project team to make informed decisions, predictions, and adjustments. However, some methods and models have *limitations of prediction*, thus it is important to *combine different methods* (Fischer et al., 2017; Ch.10). Thus, IPD suggests to use an integrated information scheduling which would encompass various methods and provide necessary tools for adaptations and adjustments according to the project needs (Fischer et al., 2017; Ch.10). Also, for a *complex and BIM managed project, a single approach may not prove to be efficient*. Thus, an early anticipation and a holistic systematic approach should be implemented to provide the project team with necessary tools.

Thus, despite such thorough methods development, Bourne and Weaver also highlight a *need for effective scheduling and construction activities controls*, together with a needed for the *methods to advance towards 21st century progress and digitalization* (Bourne and Weaver, 2018). Therefore, our study seeks to investigate further the IPD and Lean methods, and the use of 3D + time (4D) digital project models to support planning, scheduling, and construction management. Where a 4D model would provide a better visualization of project issues, thus become a support for a better understanding and for collective decision-making.

4D dimension concept and 4D BIM establishment

In parallel with works on 4D CAD and 4D Models, Lee et al. propose a road-map for nD (multiple dimensions), where the 4D CAD is considered as a departure point for further nD development, they outline a *nD model as a 3D model with other dimensions assembled into a holistic model corresponding to the project development objectives*, and nD is based upon the emerging BIM, and identify the *dimensions as: time, cost, sustainability, accessibility and maintenance* (Lee et al., 2005).

From an elementary point of view, when a “3D” dimension of the enriched virtual model of a project is bonded with a dimension (or a concept) of “Time” they are referred as “4D”. Therefore, when schedule and information related to it is combined with a 3D Model (x, y, z geometry & related spatial model elements data) they become a 4D model, and they create *4D link* to the project data. Thus, the

4D as a dimension, would be representing the dimensions of “3D” and “time (schedule)” connected and represented through the animation and/or a time diagram, progress line, and task list.

An added value of 4D is a “new component” created by the link established between the elements of 3D model and schedule tasks, which combine assigned data, and technically create their own new concept of a “4D link”. Naturally, certain kinds of data may be included in time and 3D dimensions, and therefore be “merged” in a 4D model, including tasks and elements IDs, start and end date, resources required, etc. However, the data types depend on 4D uses and 4D tools choice.

The research around “3D + time” concept introduced multiple terms to outline the subject, and it refers to it sometimes as “4D CAD”, “4D model”, “4D simulation”, “4D planning”, “4D planning and scheduling”, “4D BIM” or “4D technology” depending on a research origins, subjects, and scope. Following the advancements of IT, CAD and works towards Building Product Models, the 4D concepts and early experiments seem to appear in late 80s as an experimental tool in industry for collaboration between Bechtel Corporation and Hitachi Ltd to develop the Construction *CAE/4D Planner software* (Rischmoller et al., 2001), and before the introduction of BIM or nD BIM.

A study by Koo and Fischer defines that a **4D CAD**: “... model results from the linking of 3D graphic images to the fourth dimension of time.” (Koo and Fischer, 2000), also it may represent not only a model, but also a **4D simulation**, as “... 4D CAD represents a type of graphic simulation of a process” (McKinney et al., 1996). Thus, both terms evoke the 4D link, yet not focus on the same elements. Another study of various construction projects use-cases on 4D benefits by Fischer describes: “**4D models allow project stakeholders to work out many design and construction issues in the computer model before actual construction, maximizing project value to owners and making it more likely that the project will be performed as planned and designed.**” (Fischer, 2000).

A study following the abovementioned industry perspective on 4D research reports on **4D planning and scheduling** bringing efficiency benefits to a case study project, however the study analysis also highlighted a **need to adapt work processes** and practices context (need for new approaches) to fully benefit from 4D implementation (Rischmoller et al., 2001), which presents an early indication of a shift towards digital tools use as a core, but also a need for processes and collaboration (social parts of a socio-technical system) and organizational aspects to adapt to the new digital tools as well.

From the academia perspective, a Center for Integrated Facility Engineering (CIFE) and 4D research group led by Martin Fisher investigated the use and benefits of 4D modeling, as well as worked **on new tools, technics and approaches to support 4D use** in real construction projects since 1993 (Fischer, 2000). For example, as an effort to create **a new 4D tool**, researchers describe a **4D WorkPlanner** prototype, composed of Space Generator and Time-Space Conflict Analyzer in order to propose a system that would assist project managers with decisions, analyses and conflict management (Akinci and Fischer, 2000). 4D models were also seen as a mean to create a **basis to assure continuity of use of 3D** and other elements of design information to the planning and construction phases (Fischer, 2000), thus anticipating the BIM-based design and collaboration.

Likewise, 4D study by Staub-French and Fischer on implementation of 4D schedule made with Bentley Schedule Simulator emphasizes that the Critical path method is limited, since a **link between 3D and time is not available within CPM**, however the link is critical for effective evaluation, monitoring, and coordination of construction process, however the study argues that the **new approach of 4D CAD provides a visualization of 3D+time link and fosters quality of communication, of coordination, of analysis of a project schedule and of installation process simulation as an assistance to a project team** to avoid errors and to make more productive planning (Staub-French and Fischer, 2001).

Thus, even before the establishment of BIM, the research supported by industry experience was investigating the most relevant approaches and tools to present the 4D link as a support for visualization, communication, coordination, and management. Also, during this time 4D CAD, 4D model or 4D modeling, 4D technology are the most recurrent terms.

Expanding beyond 4D CAD, Kam et al. present a more complicated implementation of 4D for design and construction in real projects as *Product Model and Fourth Dimension (PM4D)* approach which encompasses tools, standards and technologies and includes use of: *Object-oriented product modeling, 4D CAD and IFC standards, Thermal comfort and energy simulation, Computational fluid dynamic analysis, Lighting simulation, Design model checker, Environmental impact assessment software, Life cycle cost comparison, Virtual Reality* (Kam et al., 2003), they also implement Solibri viewer and checker into the approach. Such approach enables the interoperability of project models as a “core model” presenting BIM approach before the emergence of term.

With a focus on management, another study describes *4D Management for Construction Planning and Resource Utilization* very detailed as “*activity is suitably annotated with its resource requirements including material, plant, labor, workspace and cost*” thus there is an evolution of approach, where “*4D concept has been taken well beyond its original scheduling utility*” (Wang et al., 2004).

In the “BIM handbook” Eastman et al. use a variety of terms to describe various 4D related terms, for example, they summarize *4D CAD* as: “... *tools allow the contractor to simulate and evaluate the planned construction sequence and share it with others in the project team.*”; or as: “... *linking a construction plan to the 3D objects in a design, so that it is possible to simulate the construction process and show what the building and site would look like at any point in time*”; a *4D model* according to them: “... *supports communication of sequencing*”, and *4D simulations*: “*function primarily as communication tools for revealing potential bottlenecks and as a method for improving collaboration*” (Eastman et al., 2008).

Further, *4D modeling* is described as: “... *computerized methods to represent construction plans that add the temporal dimension to 3D CAD models.*” (Hartmann, 2011). Since the establishment of BIM, *4D BIM* associates the virtual *3D model of a construction project with a construction schedule* (Zhang and Hu, 2011).

Thereafter, in line with established BIM collaboration ideas, Zhou et al. consider *methodological, technological, and social challenges of collective work and models use*, thus outline the social-technical context for collaborative planning, and propose a solution (4D groupware) for *Model-based collaborative 4D Planning* with the 4DX prototype and to assist a multidisciplinary team with distributed computer-supported collaborative work (CSCW) and create interactive collaborative mechanisms. (Zhou et al., 2012).

Following the collaboration topic, but co-located, Boton investigate 4D BIM and its collaborative use, but also considers it as a part of nD paradigm, and explains that 4D CAD: “*consists of associating the scheduling of activities with a 3D model and obtaining a 4D model, usually in the form of an animated sequence in which the phases of the construction run through time.*”; but a *4D model*: “*justified by the need to simulate the construction process, in order to detect and anticipate implementation problems: this is called 4D CAD-based simulation or simply 4D simulation*”. (Boton, 2013). And from project team members perspective, Ding et al. explain *nD model as a model that provides a database for all project stakeholders* to access required information through the same for all parties system, and allows more cohesive and efficient work (Ding et al., 2014). The research also highlights that due to a *dynamic nature*

of a construction process, including changing conditions, quality evaluations, site safety, a computable multi-dimensional (nD) model is difficult to establish (Ding et al., 2014).

While taking into account the development of BIM and interoperability protocols, Kassem et al. outline the limitations of available commercial 4D visual planning tools (e.g. Autodesk Navisworks, Synchro, Bentley ProjectWise Navigator), and outline a need for “... *the development of the solution within a platform that is aligned with the construction industry trend of adopting BIM technologies in particular 4D and 5D technologies and open standards such as IFC.*”, thus they propose a **4D tool for construction management** that would take into account the IFC standard and be useful for workspace management (Kassem et al., 2015). This approach continues to support BIM interoperability requirements and to assist in multidisciplinary collaboration.

In order to emphasize on decades of previous research on 4D, Gledson and Greenwood examine the 4D terminology variety, considering all the points of view agreeing on 4D model linking 3D BIM model to a construction schedule, they also emphasize on **4D planning** in particular which: “... *involves linking a time schedule to a 3D-model to improve construction planning techniques*” through visualization, analysis and error control (Gledson and Greenwood, 2016). Thus, they underline a specific use of 4D model for planning.

As a part of work on Integrated Project Delivery, Fischer et al. describe that an animation of a construction sequence presents a **4D simulation** “... *connects the building elements in the model with information from the schedule to reveal what will be built when, where, by whom, and with what.*” (Fischer et al., 2017; Ch.12).

The latest terms definitions tend to encompass in a more comprehensive way all the potential uses of 4D, describing **4D modeling** as one that: “... *integrates 3D model with project time schedule to provide virtual simulation for identifying spatio-temporal problems earlier in construction projects.*” (Altun and Akcamete, 2018). Or the BIM project execution planning guide describes **4D Modeling** as “*A process in which a 4D model (3D models with the added dimension of time) is utilized to effectively plan the phased occupancy in a renovation, retrofit, addition, or to show the construction sequence and space requirements on a building site.*” (Messner et al., 2021).

The presented variety of concepts portray the evolution of 4D from an idea, experimental tool, and approach into a part of a BIM modeling and management with emphasis on 4D BIM use for schedule, activities and requirements integration into a “core model”. Thus, we further refer to **4D BIM as a model enabling a link of 3D BIM model to program, planning, schedule information, to construction process requirements and monitoring**. The 4D BIM particular value is in 4D visualization of the link, and its potential to improve project team collaboration and to enhance efficiency of decision-making and construction; as well as in its potential to assist with Lean construction and IPD (see 1.3).

Furthermore, latest research investigations expand beyond 4D BIM and nD, since there is a potential for exploration for **new generation of monitoring platforms, intelligent semantic platforms and agent driven socio-technical platforms**, where in addition a nD model is a transition basis for a semantic digital twin (Boje, Guerriero, et al., 2020), and closer convergence with IPD (Elghaish and Abrishami, 2020).

1.1.3.1 4D BIM adoption and uses

4D BIM adoption

In 2010, Dawood identified that to foster 4D technology diffusion (adoption) in AEC there is a *need to overcome legal, technical and cultural barriers* (Dawood, 2010). Various studies have been conducted across the globe to investigate in particular 4D BIM diffusion/adoption are reporting *relatively low numbers* (Mahalingam et al., 2010); Boton et al., 2013; Kubicki and Boton, 2014; Gledson and Greenwood, 2016). The percentage rates of 4D BIM diffusion progress and indicate the market advancement and space for further studies. In addition to 4D studies, a European context study of BIM dimensions assessment revealed that there is no confusion among academics or practitioners about 4D connecting 3D to planning or scheduling, and 5D to cost, yet the study reports a lack of clarity on meaning of 6D or 7D brings confusion (Charef et al., 2018).

According to the data from international Smart market report, many contractors have committed to the *integration of models with schedule on design and pre-construction phases*, and such integration is perceived as one of leverages on BIM use, with an average percentage of 29% for the 9 largest construction markets, and with 39% in France (McGraw Hill Construction, 2014). Yet, the report does not present in detail the data collection methods.

Many pilot projects conducted a successful application of 4D simulation for communication on *construction sequencing in the USA, Finland, and China* (Hartmann et al., 2008). An IT barometer survey of *Luxembourg's context conducted in 2014 reported that one-fifth of respondents is familiar* with a concept of 4D (Kubicki and Boton, 2014). *In Australia, the adoption of 4D is only emerging*, and companies tend to delegate their 4D and 5D related tasks to external to the company specialists (Pyung et al., 2016). Recently, a one of the most detailed studies on 4D BIM diffusion/adoption dynamics by Gledson investigated UK's current context. The study's survey results report that in *UK there is a high level of BIM maturity and that more than half of participants currently use 4D BIM* in their practices. Also, 4D adoption was either an *authority decision or a collective consortium* decision (Gledson, 2015) (Gledson and Greenwood, 2017).

The adoption and implementation of *4D BIM and nD BIM are a dynamic, continuous process*, which are highly dependent on local policies and on market conditions. Every geographic and legal context has its own subtleties and limitations, but the global digital project design and management shifts and problems are similar for many markets, yet the global tendencies frequently reflect on a local context. In addition, the distinction between diffusion and adoption are not always outlined in analysis methodologies.

Like any data surveying the state of the art, the data on 4D BIM adoption must be updated to provide more accurate and relevant to the current state results. Nevertheless, the presented studies outline observations from the previous studies.

4D BIM uses

Ahmadi and Arashpour analyze 4D BIM planning topic in research and outline its strong connection to *BIM, collaboration, BIM implementation, adoption, productivity, analysis, cost and time research topics* (Ahmadi and Arashpour, 2020).

Providing a global perspective, an analysis of 3D/4D uses (applications) from 26 cases (1996-2005) of different types and sizes reports usefulness of the models for: *virtual design review, analysis of design options, building operations, cost estimation, construction operations analysis, construction document*

production and bid package preparation (Hartmann et al., 2008). During the construction phase 3D/4D assisted with such tasks as:

- *tracking of construction,*
- *coordination of contractors,*
- *management of construction site and schedule constraints,*
- *planning of construction operations and methods,*
- *maintenance of facility operations (Hartmann et al., 2008).*

Hence, most often 4D is used to visualize the planned construction process or reveal clashes, but again other uses have ***not been fully integrated into common practices*** (Hartmann et al., 2008).

Further, Zhang and Hu propose three types of 4D applications:

- *dynamic safety analysis of time-dependent structures,*
- *conflict analysis and management of schedule/resources/cost,*
- *collision detection of site facilities (Zhang and Hu, 2011).*

According to another report from literature and form practice the 4D is also ***mostly used as a process visualization support*** (Boton et al., 2013). Dave (2013) outlines that 4D simulation use at early project development phases during the conceptual design and feasibility study may assist with ***variability reduction and constructability***, or in case of proximity of a project site to operational buildings 4D may be used to ***evaluate impacts of construction activities on nearby buildings*** (Dave, 2013).

An overview of BIM uses in construction use-cases and studies (1994-2019) reports that most of the topics were ***dedicated to scheduling, then to construction simulation and site monitoring, or visual communication***; another topics represent less than 10% of the selected research items (Boje, Guerriero, et al., 2020). Thus, the scope of the global perspective is quite large, yet the focus always stays on the construction process and necessary tools to efficiently support it.

Gledson and Greenwood present a study of 4D BIM diffusion and adoption (in UK AEC context), the data analysis suggests that 4D would be rather used in large companies, and that perceived 4D BIM advantages against construction planning process are mostly in:

- *communicating the construction plan,*
- *planning the construction sequence,*
- *planning the logical dependencies,*
- *communicating project timescales (Gledson and Greenwood, 2017).*

Fischer et al. propose to use 4D simulations as a part of Integrated Project Delivery for more informed decision-making approach, and to:

- *visualize and compare various construction scenarios,*
- *visualize and manage safety hazards,*
- *manage construction sequences and logistics,*
- *manage time and space conflicts (Fischer et al., 2017; Ch.12).*

The studies of possibilities and application of 4D, Guerriero et al. proposed the ***4D BIM uses***:

- *4D Scheduling,*
- *4D Clash Detection,*
- *4D Safety Management,*
- *4D Site Lay-out & Environment Management,*
- *4D Constructability Management,*
- *4D Monitoring and 4D Visual communication is core use (Guerriero et al., 2017).*

These uses follow the BIM uses, yet their main purpose is to highlight the 4D BIM use-cases.

4D BIM and project phases

Like the BIM uses, the 4D BIM uses can be *implemented into a project following its' life cycle* and objectives. Yet, *4D BIM mostly occurs at the pre-construction phase* (Zhang and Hu, 2011). However, the availability of 3D and time management information and other accompanying data are even occasionally *valuable not only for construction, but also for design, project management and negotiations*. For example, when the first design shapes or concepts emerge it is already possible to bond the with the project duration or delivery date estimations to forecast construction phases and sequencing as 4D Scheduling. Further, when the construction is started the scheduling becomes more detailed and tasks oriented and may be accompanied by 4D Construction management (administration).

Construction projects with 4D implementation assist some large construction projects and many pilot projects, since the use of 4D BIM provides possibilities of more visual cost and errors control, and LPS® to make scheduling and coordination more efficient. Nevertheless, as a process simulation the 4D model should be well-defined and detailed. Since LOD mostly refers to graphical data, there is a distinction of LOD from LOI (level of Information) in the literature, and a more precise term for a 4D BIM model would be referring to Level of model Development or Definition through the project life cycle. Tolmer et al. introduce *“LOX” to encompass level of detail, of information and of abstraction* (takes into account the stakeholder point of view) which presents a quiet composite approach to include dimensions: geometric complexity, dimensionality, appearance, semantic, presence, attributes (Tolmer et al., 2017). Such an approach brings a broad spectrum of elements for analysis and consideration regarding concepts, tools, and project, yet it is not coherent with our research scope.

A study of 4D simulation use at collaborative team meetings for a project use-case in Luxembourg at pre-construction and construction phases to coordinate site work, logistics and details, reports a *need to use of multiple graphical levels of detail for decision-making*, and a need for adjustment of planning level of development *4D LOD* (Boton et al., 2015).

Further, Guevremont and Hammad present guidelines to provide more refined and adapted 4D simulations with relevant level of development:

- *4D-LOD A: Demonstrative/Summary with month to week schedule,*
- *4D-LOD B: Major work coordination and feasibility with week to day schedule,*
- *4D-LOD C: Contractual baseline at the time of bid with day to hour schedule,*
- *4D-LOD D: Operational field work with hour to minute schedule,*
- *4D-LOD E: Detailed equipment movements and workspaces with hour to minute schedule* (Guevremont and Hammad, 2019).

The proposed approaches about 4D Level of Development emphasize the details of the graphical and schedule information aspects, and the requirements to assist with digital supports for decision-making. Naturally, the 4D BIM model is a part of the BIM approach, and 4D BIM potential introduction and use follows the phases of a BIM model LOD (Figure 6). More precise use of 4D levels of detail follows the project phases.

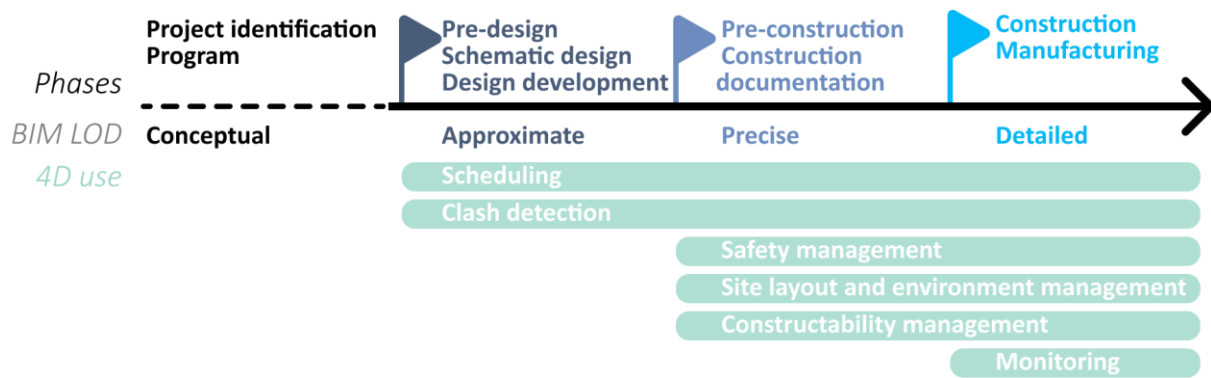


Figure 6 Schema of potential 4D use through the project phases and in coordination with BIM level of detail (LOD)

Such 4D BIM uses as 4D Scheduling and 4D clash detection may be possible even with an approximate LOD at Pre-design, Schematic design, and Design development, and become of a more use through the project grows. At pre-construction and construction documentation development when the BIM is precise the 4D may be used for safety management, site layout, and environment management, and for constructability management. Finally, at construction phase the 4D-based monitoring may be used as well. The operation and maintenance phase are not in the scope of this research due to the phase specifics and main relevance in a domain of facility management.

1.1.3.2 4D BIM benefits and challenges

Project visualization, communication, and collaboration

Since every project and project team are unique, the benefits from 4D BIM implementation would depend on the set workflows and demands, however it is possible to outline the benefits in general. One of the most cited benefits from 4D CAD or 4D BIM implementation are the impacts on clearer *project visualization, improved communication, and collaboration*. From a more focused on 4D use experience perspective, one of the early case studies on implementation of a 4D CAD Simulation concept reports on benefits of *quick perception of the geometry* by different people as an emergent form of communication (Collier and Fischer, 1995). According to case studies feedback (Haymaker and Fischer, 2001), after the sessions with 4D model, different members of a project team *increase commitment to collaboration and to resolution of project problems*. 4D may provide a benefit because it *outlines settled parts of a project within the points to develop or rethink* (Haymaker and Fischer, 2001). According to Eastman et al. 4D BIM provides “improved communication inside a project team through a 4D model encompassing temporal and spatial aspects of a schedule” (Eastman et al., 2011).

Koo and Fischer highlight that *conventional bar chart schedules are not the most effective* tool to comprehend all aspects of construction project processes, nor they are initially designed as a tool to represent an association between project model elements and related to them activities, unlike the 4D model (Koo and Fischer, 2000).

Kam et al. propose comparison of 4D CAD use with conventional practices of project scheduling, and reports 4D benefits in categories of project (Table 1) (Kam et al., 2003).

Table 1 4D benefits in categories of project according to (Kam et al., 2003)

| Categories of project | 4D benefits |
|-----------------------|---|
| Organization | Fostered early interdisciplinary collaboration and exchange of expertise |
| Collaboration | Expedited design coordination and resulted in faster generation of project solutions |
| Information sharing | Minimized data re-entry, improved accuracy and quality |
| Decision support | Enabled team to develop multiple alternatives early in the project and provide additional valuable life cycle parameters to the decision-makers during early project phases |
| Quality | Improved design accuracy and shifting some of the project team's efforts from producing traditional outputs to more value-adding work |

Another comparison study by Candelario-Garrido et al. examines 4D-based planning use with and the conventional graphic planning method use, confirms the previous authors statements that **4D use:**

- *increases planning efficiency,*
- *provides more effective visual control and understanding of the construction process,*
- *assists with decisions on early project stages,*
- *increases efficiency of construction advancement updates.*

However, it also reports that *the conventional planning method is less time-consuming comparing* to the 4D (Candelario-Garrido et al., 2017).

Despite the presented benefits, Dawood suggests a need to argue on 4D BIM implementation benefits in a measurable clear way through a framework offering KPI calculation and categories (time, safety and client satisfaction, planning efficiency, communication efficiency, rework efficiency, cost, team performance, productivity performance), and reports findings from use-case analysis that, for example, *4D use saves 30% of meeting time due to improved communication* (Dawood, 2010).

Access to project information

Additional perceived benefits from 4D CAD or 4D BIM implementation are the impacts of it on more *accessible information on the project for all project stakeholders, and other parties*. According to Eastman et al. Several project documents, new connections and actors issue the complexity of project data. A 3D BIM model is frequently the core of a project (like a digital core of a socio-technical system), and it is linked to all other data on the project. This data integration builds a number of nD dimensions into a *holistic model, which covers the entire life cycle* of the project (Lee et al., 2005; Hartmann et al., 2008).

Even though 4D BIM provides "an access to project information for multiple stakeholders" (Eastman et al., 2011)., and should be accessible to all project team members, first analysis outlined that in most cases the 4D use stayed limited to only one purpose at one project phase (Hartmann et al., 2008), and stays still true to many cases, yet there is a shift in common practices brought by 4D BIM implementation due to involvement of *different project teams early* during a project design and (Ahmadi and Arashpour, 2020).

Furthermore, a 4D construction simulation improves project *understanding and workflow for a construction team*. Thus, the study by Candelario-Garrido et al. concludes that 4D simulation represents

a valuable graphical tool for all project stakeholders and participants and *an information center to make a clear decision* which would *benefit from collective knowledge and experience* (Candelario-Garrido et al., 2017). Also, an access to a 4D visualization of construction fosters the *better understand of project information and workflows by the construction workers*, which influences their productivity and efficiency, in addition, the experiments with portable distant collaboration devices on site show positive feedback from construction professionals (Svalestuen et al., 2017).

Also, for some complex projects, 4D models are not only useful for design and construction teams, but also for a *dialogue with the local authorities*, and it is used to *review the work sequence and improve constructability* (Fischer and Kunz, 2004).

Analysis, construction management and monitoring

Another often cited benefits from 4D CAD or 4D BIM implementation are the abilities to run *schedules, models, and construction scenarios analysis, to include 4D into construction management and monitoring*.

Penttilä notes that advantages from 4D/nD use for construction management is increased *accuracy in quantity take-offs and highlights of overlapping activities*, and for general project understanding there is a better *process and visual control* (Penttilä, 2006).

According to Eastman et al. 4D BIM provides *“an ability to compare schedules and track construction progress, to improve site logistics and trade coordination”* (Eastman et al., 2011), also a 4D schedule improves understanding of various requirements not only at one phase of project development but *throughout project life cycle* (Ghaffarianhoseini et al., 2017).

4D BIM is frequently recognized as a *complementary scheduling instrument* (Rolfesen and Merschbrock, 2016), To help a project team manage required materials and equipment at the right moment to sustain productivity with less delays (Ghaffarianhoseini et al., 2017). Thus, with 4D BIM-based planning the project team may simulate construction in virtual environment and to *manage resource requirements, availability, safety* (Bourne and Weaver, 2018); or *as management instrument* since it provides *accurate requirements data* (Malacarne et al., 2018).

In addition, when implemented with integrated project management approaches, the 4D BIM enhances the project planning and assists reduction of resources waste, combined with IPD it may benefit the project team with improved coordination, interoperability of project planning and control of time and cost at different points of project life cycle (Aminu Umar et al., 2015).

An analysis of research on 4D by Ahmadi and Arashpour published in 2020 summarizes a broader list of 4D BIM benefits from the literature:

- *enhancing project performance,*
- *efficient planning and scheduling,*
- *detailing the project phases,*
- *generating multiple plan scenarios,*
- *being used for bidding purposes,*
- *enhancing the ability to adapt future and network changes,*
- *utilizing for 4D BIM in line VR and mixed reality technologies,*
- *using for 4D BIM in line with 3D point cloud scanning technology,*
- *being an initiative-taking platform for risk detection,*
- *being proactive in directly advising and addressing solutions for project issues (Ahmadi and Arashpour, 2020).*

Challenge of innovative technologies, processes, and skills

Since the emergence of 4D modeling, researchers and industry identified several issues and challenges related to 4D implementation. There are issues regarding technological solutions, issues of need for more integrated and collaborative approaches and processes, and of new skills development to benefit from all the innovations.

These issues and challenges expand into a list of barriers identified through investigation on 4D implementation in real construction projects use-cases made by Dawood in 2010 is still truly relevant, even if some dynamics have changed, it reports on barriers regarding:

- *lack of a standard tool for information sharing,*
- *too significant amount of time and attention required to upgrade the model,*
- *lack of system compatibility, standardization,*
- *lack of 4D skilled professionals,*
- *too significant time and money involved in training required to upgrade the skills of work force,*
- *resistance to change within the industry and to go through a new learning curve,*
- *construction companies are not eager to invest in Research and Development,*
- *lack of willingness to adopt technology (Dawood, 2010).*

Regarding the requirements for technological solutions, even early studies of 4D use-case summarizes a need to ***automate schedule preparation*** (Koo and Fischer, 2000), to surpass this problem many research and commercial solutions work on automation solutions. Indeed, a ***creation of 4D models may be time and recourses consuming***, and requires task information generation and mapping automation. Thus, Altun and Akcamete present an approach for automation of 4D Tasks IDs assignment, with an algorithm in Dynamo^{iv} linked to the BIM model in Revit the 4D Task ID parameters are assigned to BIM model elements with a pattern of “Assembly Code—Family Name—Family Type—Level” based on task’s properties (Altun and Akcamete, 2018). The proposed method illustrates the potential of such approach, yet has some technical limitations, the authors emphasize that ***a well-defined framework, templates and levels of development are crucial for automated 4D tasks assignment*** (Altun and Akcamete, 2018).

To answer the automation and levels of development issue, Malacarne et al. develop a framework with 4 levels of complexity to encompass all aspects, and propose “PRECISE” methodology for BIM 4D modeling and managing construction process, where through an automated tool a model object is associated with a specific working task in a specific location to ***create a coherent 4D BIM model with relevant LOD*** (Malacarne et al., 2018). Yet, this practice is not a part of common approaches.

A study by Zou et al. identifies a gap that the industry has ***not yet reached a common convention on visualization of different risks types*** (structural, construction, health and safety, financial, environmental, etc.) since it is focused in particular on the field of studies on risk management and visualization with 4D BIM to improve communication within multidisciplinary team (Zou et al., 2019), however the same ***lack of conventions*** is relevant not only to risk management.

Regarding the issues of need for more integrated and collaborative approaches and processes, early 4D studies outline a need for an approach that would provide an access to ***4D modeling at early design stages*** to expedite the 4D model development and use (Koo and Fischer, 2000). In addition, there is a need to ***develop more integration of all the uses***, there is a need to ***adapt the technology solutions*** that would be enabling all the uses and a need to also ***adapt the work and business processes to benefit from 4D*** implementation (Hartmann et al., 2008). To foster the change AEC industry must overcome the

^{iv} visual programming addon for Revit

lack of standardized procedures or software to solve organizational and multidisciplinary collaboration problems (Malacarne et al., 2018).

Even though BIM brought many benefits to project design, yet its use led to a *disconnect from time and space at a construction site* (Laakso and Kiviniemi, 2012), even though the implementation of 4D tools increases (Eastman et al., 2011). A 4D based quality management model would encompass *product, organization and process* from a BIM model (Ding et al., 2014). Lin and Golparvar-Fard point out the *inefficiency of tracking work-in-progress and information communication on construction sites*, and experiment with superimposition of image-based 3D point clouds with 4D BIM to *automate construction progress tracking* and to highlight locations at risk by use a web-based BIM + Lean tool for mobile tracking and decision-making (Lin and Golparvar-Fard, 2016). They also report from construction team collaboration meetings that BIM use was successfully extended into the *construction phase for proactive monitoring* and real time feedback, moreover the *location-based monitoring amplified collaboration* at weekly meetings (Lin and Golparvar-Fard, 2016).

Regarding the need for new skills adapted to technologies and approaches, a study by Rolfsen and Merschbrock presents feedback on use of Gantt charts, Flowline charts and 4D BIM in a construction project case study through TAM methodology analysis on perceived *usefulness, perceived ease of use and behavioral intention* of the tools. Their findings report that a *Gantt chart remained the main tool* for daily progress monitoring and critical pass follow ups, yet its use was messy for a high number of activities, perceived as a “all-round” management tool; on another hand a *Flowline chart was useful for scheduling concurrent activities*, yet difficult to understand for some professionals and is more of a “complementary” scheduling instrument; finally the *4D BIM was a powerful visualization* tool, especially for new construction personnel on site, yet perceived as *a difficult tool and also seen as a “complementary” instrument* (Rolfsen and Merschbrock, 2016). Thus, the study reports on 4D BIM *a lack of technology acceptance even in advanced BIM projects*, and a perception that 4D implementation *requires advanced digital skills*, which fosters its use during early stages but not yet accessible for construction site personnel (Rolfsen and Merschbrock, 2016).

Malacarne et al. also outline that 4D BIM modeling *requires high skills in modeling and collaboration* relatively hard to acquire as barriers for implementation (Malacarne et al., 2018), yet once a collaboration protocol is established, the skill set would be adjusted to the needs or modernized with education. A study by Gledson, despite reports on high level of 4D BIM diffusion and adoption in UK, also concludes that there is *still a need to explore more implementation cases and perceptions of 4D BIM* from real and intended users (Gledson and Greenwood, 2017), since 4D modeling is still perceived as “... *a demanding visualization methodology*”(Ahmadi and Arashpour, 2020).

Interesting feedback on 4D BIM usefulness perception comes from a survey conducted by 4D Collab project in 2018 among AEC professionals of various professions, reports that the respondents with few BIM experience tend to identify the *visual communication* as a major benefit from BIM implementation into their practices, *however the more experienced with BIM respondents highlight its value at construction process management*. In the same way, 4D value is perceived as a support for *4D Visual communication*.

4D BIM uses are reliant on tools, on project stakeholders’ expertise and collaboration. Their implementation *fosters new collaborative project workflows*, and in our research scope they also outline technological and methodological needs for BIM-based collaborative decision-making at the meetings. The BIM project execution planning guide outlines that for 4D BIM efficient use *a project team would require:*

- *knowledge of construction scheduling and process,*
- *quality schedule as well as knowledge of 4D software,*
- *ability to interact with the model and review it. (Messner et al., 2021).*

More detailed identification of 4D BIM implementation needs and requirements is provided further in section 2.2.2.

Key points of 1.3.2

IPD, Lean construction and BIM/4D

- Project time management may be perceived through three types of activities: program, planning, scheduling. Which encompass various levels of detail relevant to various management and development phases requirements.
- Project scheduling may be approached with a variety of methods developed to fulfill specific goals. For a complex and BIM-based project the use of one method may not be efficient, but a combination of various methods aiming to present progress, provide alternative scenarios, highlight relations and dependences, and allow location-based control. In addition, from an enhanced collaboration perspective and the most accurate operations control, the most common CPM diagrams do not present enough details or provide a connection to a BIM model.
- Various concepts describe 3D and time bond in the literature emphasizing a model, a simulation, a process, a semantic model. In our study we refer to “4D” or “4D BIM” as a model enabling a link of 3D BIM model to program, planning, schedule information, process requirements.
- 4D BIM uses are naturally a part of BIM uses, however they have some specifics relevant to the “time dimension”. The most cited uses are visualization and monitoring in the core of implementation, further scheduling and clash detection occur during design and pre-construction; they are followed by site Layout, environment, and constructability management. With the project development advancement, the LOD of a BIM model and precision of planning and schedule grow, therefore the LOD of a 4D BIM advances as well, and enables more 4D BIM uses.
- Despite the benefits of improved visualization, planning and control, 4D BIM has not yet been fully integrated into common practices. There is a need for improved visualization considering not only CPM but also another method of project scheduling and 4D BIM use, as well as the phases of the project. In addition, there is a need for democratization of the access to 4D and its integration into digital workflows. In addition, in integrated projects planning is a collective and collaborative activity which must be supported by relevant and customized digital tools.

Summary of 1.1

Digitalization and BIM/4D in AEC

- The continuous growth of digitalization in AEC fosters many changes to the established work practices, tools, approaches to design and construction. It puts a project digital (virtual) model in the “digital core” of shared information and exchanges, creates a common ground for all project stakeholders.
- Since a design and construction project is always a team effort, the project data accessibility and with digital tools its interoperability inside the project team are crucial for efficient exchanges and workflows. Thus, research and industry efforts from last decades advanced towards standards to assure the data interoperability and collaboration protocols.
- BIM became an established approach to project design and construction, an expanded from enriched 3D model to more complex system of variety of data united in a shared model. The model “dimensions” expand to time, costs, and sustainability management, and even heading towards new Digital twin paradigm. As a digital tool and a method to assure interoperability, BIM becomes the “digital core” of a socio-technical system, a support for multidisciplinary collaboration.
- Despite the wide adoption of digital tools and of BIM, and potential benefits for project team collaboration efficiency and construction efficiency, the uses of 4D BIM stay yet limited. Partially, it is due to the complexity of information represented by 4D Model, but as well due to lack of approaches and tools, which would foster its use for collaboration and decision-making.

1.2 Collaboration and BIM, Lean construction and IPD overview

1.1

1.2

1.3

The first focus of our study is on 4D BIM use; however, our investigation also encompasses issues of collaboration subject, presenting the second focus. Collaboration is a part of project design and construction processes, as well as it often represents important means for efficient decision-making. Various aspects shape the frame of collaboration including approaches to organization and work management, methods, and tools choice. The digitalization and BIM propose tools and workflows to enhance the multidisciplinary collaboration. They also foster changes to traditional AEC projects design, construction, and management approaches, and bring changes to collaboration process of a project.

In parallel with the advancements in technology which fostered BIM development and adoption, the advancements in project and construction management fostered emergence of innovative approaches, methods, and tools for more efficient and integrated project delivery, as well as efficient construction and fabrication, such as Integrated Project Delivery (IPD) and Lean construction.

The aim of this section is to outline the subjects shaping the scope of our study as well as to present the key concepts relevant to our research. Therefore, first the section emphasizes the concepts related to collaboration definition and aspects in AEC, and it outlines studies of BIM collaboration (1.2.1). Lean approach for more efficient construction management and collective planning also presents the concepts funding our study. Therefore, the following section also overviews Lean construction principles and planning tools (1.2.2). In perspective of linking the concepts and studying 4D-based collaboration, the section emphasizes the concepts as well related to IPD approach and collaboration (1.2.2).

1.2.1 Collaboration and BIM

The following subsection first presents an outline of collaboration definition to portray various understandings of collaboration in AEC and the associated with-it concepts, with an aim to set the study frame and to outline the place of synchronous co-located collaboration (1.2.1.1). Second, the subsection emphasizes the socio-technical collaboration and BIM relation, it outlines the challenges of BIM complexity, and overviews the approaches to BIM collaboration studies.

1.2.1.1 Collaboration in AEC

Collaboration outline

Various kinds of working together are required from a team to develop a project; the kinds like networking, coordinating, cooperating, and collaborating. They imply an increasing level of interactions among actors, of their collaboration, and different levels of working together may be emphasized **as a collaborative continuum** proposed by Arthur Himmelman (Figure 7) (Himmelman, 2004). Where the **networking is at a basic level** of working together supporting the information exchanges, which it is followed by the next level **coordination** with team members altering their activities to achieve the task, then **cooperation** relies on sharing resources and **the highest level is collaboration** (Himmelman, 2004). *Therefore, the distinction between these processes represents not only an activity type and organization, but the basis, aims and tools of each process as well. AEC project development would require all the elements of collaborative continuum; however, the scope of our study is on collaboration.*

According to Himmelman: *“Collaborating—exchanging information, altering activities, sharing resources, and enhancing the capacity of others for mutual benefit to achieve a common purpose.”* (Himmelman, 2004). This definition is not specific for AEC BIM-based collaboration, yet it encompasses all the important aspects of the term. During a collaboration, all **project stakeholders share the same environment** (digital or analogue) and **shared vocabulary for work process and project information** development (Achten, 2002; Wilkinson, 2005).

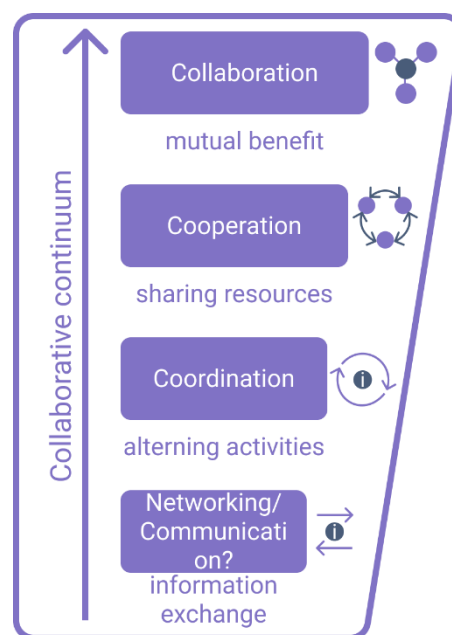


Figure 7 Schema of collaborative continuum (adapted from (Himmelman, 2004))

Despite the vast research on collaboration development, sometimes in literature the concepts of “cooperation” and “collaboration,” or even “partnership” is not necessarily distinguished in AEC, and are referring to the same idea of people working together to achieve a common goal. Regarding in particular AEC project meetings, a study by Tory et al. refers to *coordinating design* elements, and defines it as “... *the process used by a design team to identify and resolve conflicts and potential issues between different elements in a building design to ensure that the different systems work together to meet the requirements set by the client*” (Tory et al., 2008).

From a perspective of *BIM-based collaborative project design*: “*Collaboration involves the ability of the different participants to work on their part of the project using their own particular ways of working while being able to communicate with the other participants to bring about a common objective, i.e. the design of the building.*” (Isikdag and Underwood, 2010). However, collaboration in AEC is not only limited to design development, but to other important processes as well.

Hughes et al. investigated meaning of *collaboration within UK AEC industry context and* reported that “partnering” and “collaboration” are not always used with a distinction from the point of view of AEC professionals: the study outlines that *different members of a project team with different roles have different perspective upon the subject*. Thus, the investigation provided a summary of understanding of the term by AEC professionals of different project disciplines, and provided a definition encompassing essential aspects: “*Collaboration within the UK construction industry is a non-adversarial team based environment, where through the early involvement of key members and the use of the correct contract, everyone understands and respects the input of others and their role and responsibilities.*” (Hughes et al., 2012). This definition outlines the importance of collaborative environment, which is supported by legal and organizational structures.

Furthermore, Hughes et al. highlight the importance of the shared systems, dialogues, risks for mutual trust and collaboration establishment “... *where information is shared, problems can be solved together and everyone contributes towards a common aim motivated by a fair method of pain share gain share to produce a win-win outcome.*” (Hughes et al., 2012). This vision of collaboration presents a broader perspective on the subject, as an environment with the description of important aspects like sets of roles, rules, methods, and a recurrent focus on common goals.

With further investigations on the subject, Poirier et al., provide an overview of research on collaboration subject in AEC and compare it to other domains, outline that there is a lack of consensus upon the definition of collaboration, and the lack of structured perspective or body of knowledge in particular to AEC sector, however its frame is well determined. They provide a frame for definition of *collaboration concept*: “... *as a system comprised of four interacting and mutually adjusting core entities: structure, process, agents and artefacts that are conditioned by a fifth, entity: context.*”, as well as “*to collaborate is to share expertise*” (Poirier et al., 2016). Also, according to Poirier et al., collaboration is not a static “result of an effort” but *a dynamic and evolving process*, which follows the project development phases, aims and team involvement. This approach investigates collaboration as a more cohesive understanding of multiple aspects of collaboration and includes context into the theoretical framework. From the Integrated Project Delivery perspective “*Collaboration is a community of people working together to achieve a common goal.*” (Fischer et al., 2017; Ch.13). Such outline of collaboration emphasizes the importance of the common goal and of the project team members, rather than of a work process itself.

Collaboration as a study subject has grown significantly. Santos et al., emphasize form a bibliometric analysis of BIM research categories from 2005 to 2015 that *Collaborative Environments and*

Interoperability category had the most papers published, with particular interest to the subject arising from 2012 (Santos et al., 2017). Which only highlights the aspiring interest to the collaboration subject, and development of various understandings of the term as well. A bibliometric review by Oraee *et al.*, studies collaboration in BIM-based construction networks through a lens of a *collaboration pentagon* to include *social, technical and project management aspects*, and reports that the most studies are focused *on process, then on context and team, and less on actors or tasks* (Oraee et al., 2017). This study provides categories and tools to analyze collaboration, and outlines that most of the approaches focus on specific aspects.

Synchronous co-located collaboration and decision-making

The collaboration may *synchronous or asynchronous, co-located, or distant*. Many researchers focused on issues of collaborative design with shared digital models or BIM networks, this research turns the focus towards *co-located synchronous collaboration*, which appears at project meetings *for project review, value engineering and decision-making* supported by *BIM project documents and digital interactive interfaces*. Hence, we study collaboration as a part of usual AEC project delivery practices, as an essential part of effective BIM implementation and as a collective user experience with a digital interface. Where collaboration presents means for efficient project delivery, for decision-making, but also a requirement that shapes BIM documentation, digital supports, and work process.

Team meetings and collective decision-making have always been a part of construction project development, where multidisciplinary cooperation and collaboration require a significant effort from project stakeholders (Staub-French and Khanzode, 2007). For several decades, project development has used digital tools and Building Information Model (BIM) as common instruments (Kensek, 2014). A construction project team holds the tools and methods to maintain continuity and consistency of BIM workflow during design phase, however, the *continuity is frequently hindered when from design activities project stakeholders require project information to support decision-making at the meetings*.

In our study we refer to the project meetings as to *Decision-making sessions* (DMS) which unite the stakeholders for synchronous co-located collaboration, framed by shared aims of design development or value engineering, and where the participation of different stakeholders allows to benefit from collective competencies and intelligence as a decision assistance tools. In addition, digital project documents provide visualization, annotation, and modifications interactions to assist decision-making.

During a preparation for the meeting there is a step aiming to *emphasize meeting objective(s) and participants*, and preparation of an up-to-date project information and documents that would be likely the most relevant to the meeting objectives. Such preparations are a part of the digital and collaborative workflows, and represent a point of synchronization, which becomes a milestone from a meeting to a meeting conducted by various project team members.

The work of Hughes and Murdoch on roles in construction projects describe hierarchies of decisions, and they suggest that a project consists of *decision points* which can be levelled as: *policy, strategic, tactical, operational* (Hughes and Murdoch, 2001).

In more detail, according to the described hierarchy, the policy decisions on project define objectives, shape framework, and represent the highest level, next the strategic decisions define stages of project or work. On the next hierarchy level, the tactical decisions form the subsystems of activities and define project management and resources. Further the operational decisions define operations and represent subsystems of activities, yet they do not concern management problems. In addition to

providing structure for decision-making categories interpretation, such hierarchy may be compared with the schedule levels of Last Planner System described further in 1.2.2.2.

The decision hierarchy levels also involve the input and responsibilities from different project team members according to their role in a project. Depending on a project life cycle, and on decision types there will be relevant decision-making constitutes involved. Thus, Hughes and Murdoch also distinguish three decision roles systems: *operating, control, managing* (Hughes and Murdoch, 2001). The proposed systems like the decision points provide categories to understand the decision-making, and to adapt the collaboration setting the most to a meeting goal.

Table 2 Decision roles systems by (Hughes and Murdoch, 2001)

| Operating system | Control system | Managing system |
|------------------|----------------|-----------------|
| Operating | Monitoring | Coordinating |
| Cooperating | Supervising | Directing |
| Advising | Resourcing | Recommending |
| Receiving | | Approving |

1.2.1.2 Collaboration and BIM overview

Socio-technical system of BIM

Various kinds of working together are required from a project team to assure efficient design and construction project, thus there is a need for such collective work to be efficient. Naturally, project team members represent various roles and disciplines in a project, they often rely on discipline specific tools and workflows, follow domain specific protocols, legislative and organizational frameworks. Yet, one of the challenges for working together is integration of tools and workflows to make project information accessible and clear to all project team members.

Every collaboration approach values the specific features, which correspond to the needs of the work process. For an AEC decision-making a synchronous collaboration has traditionally been the most relevant approach of the interactions on a project (Wilkinson, 2005). Studies of human-computer interactions may focus on single-user or multi-user systems. The multi-users systems include people (users) working together and computers (digital supports) assisting with the work. The discipline of *Computer-supported cooperative work* (CSCW) studies and fosters design of groupware, which represents “... software that supports and augments group work” (Greenberg, 1991). In particular, AEC context, BIM is an important part of the “computer support.”

Sacks, Koskela, et al., distinguished internal design collaboration of multiple users form the same discipline or organization for development of the same project digital model synchronously, and external collaboration of multiple users as well but merge or separate models (Sacks, Koskela, et al., 2010). They also highlight that BIM may increase complexity of collaboration and foster difficulties since it relies on sophisticated technologies which require a clear frame and management to assure implementation benefits and users efficiency (Sacks, Koskela, et al., 2010).

With adoption and implementation of BIM into a common practice, project stakeholders use a single *virtual model as a source of information, as a design and modeling support*. In BIM workflow, the project development relies on a *socio-technical system* (Sackey, 2014), where *collaboration represents a human and social activity*. Miettinen and Paavola (2014) overview BIM literature and suggest that BIM implementation is seen *as a socio-technical process*, and outline that BIM technology adoption

fosters changes in collaboration organization and legal frames (Miettinen and Paavola, 2014). *They also advocate that BIM development and implementation is an open-ended expansive process, therefore there is “no final goal” to be achieved, but rather various tools will emerge and “... BIM will be used in a widening array of functions in design and building and it will be used by ever more wider networks of collaboration” (Miettinen and Paavola, 2014).*

Thus, BIM *intelligent models and information management* form the technical core of the system. The core is encompassed by social parts: *synchronous collaboration, coordinated work practices, institutional and cultural frameworks* (Figure 8) (Kennerley, 2017).

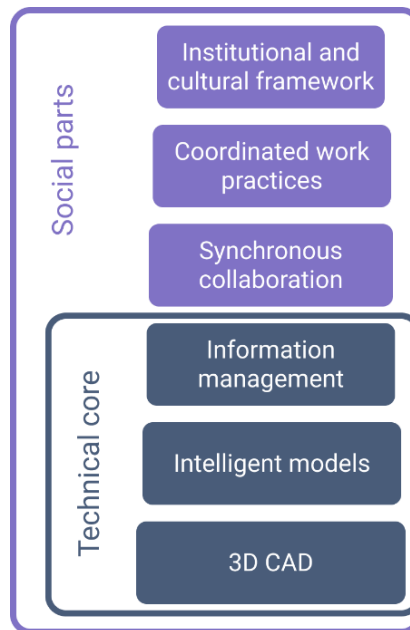


Figure 8 Socio-technical system of BIM collaboration

Regardless of the BIM advantages, the digital project management presents challenges to current practices because of the complexity of project data and highlights the need for more efficient and stronger collaboration. Naturally, every company has its own intersocial management and structure, which is created by the interactions and influences among its employees and partner stakeholders (professionals) (Jacobsson et al., 2017). These interactions between the company professionals are framed by design, construction, management methods and processes, yet they highly rely on a technical core.

BIM in the *core makes transformational effects on the established company work processes* when it enables an integrated collaboration among internal and external professionals (Jacobsson et al., 2017). Also, a BIM-based project itself, as a management approach, fluctuates from linear straight step sequence to an adaptive solution, and it is interdependent with a considerable number of Influences involved. To gain in efficiency and focus on project quality a BIM-based project may be approached with a more adaptive design, lean construction, and integrated project management.

A design and construction project progress relies on socio-technical system, where the *synchronous collaboration plays the role of the first social base* to operate the project, and it creates a work environment for further larger scale interactions. Sacks, Korb, et al., (2017) report from observations of BIM and Lean construction joint implementation that not only formal but also *informal collaboration*

proves to be beneficial for a project quality and for the design and construction companies (Sacks, Korb, et al., 2017). Therefore, an environment to foster informal collaboration, communication and interactions should be beneficial as well.

A study by Zhou et al., on distant collaborative solutions (groupware) and 4D, identify collaborative *4D planning as a correlated socio-technical activity* where “... a BIM-based model can foster both social interaction and user-system interaction for effective teamwork” (Zhou et al., 2012). However, to achieve more comprehensive description and understanding of 4D-based project meetings, a research perspective should not only consider technology and processes but meeting participants (people) as well.

Challenges fostered by BIM complexity

With new benefits and opportunities from BIM and digital tools, design and construction professionals adapt their practices to face new challenges. For example, *the increase of the complexity of project data* and BIM data with project progress may become challenging to manage. It would require an efficient work process organization. Therefore, the AEC industry seeks to implement more efficient management methods into the current work of project management team, of design and construction teams. The teams also have more emphasis on a project quality. Yet, on another hand according to Eastman, BIM management and processes are a solution to “increasing pressures of greater complexity, faster development, improved sustainability while reducing the cost of the building and its subsequent use” of modern AEC projects. (Eastman et al., 2011).

The complexity of BIM encompasses *project complexity* (design, function and structure, construction method, ambition of the project schedule, project size/scale, geological conditions, and neighborhood environment) and *organizational complexity* (stakeholders interactions, design aspects, engineering, and management) (Wood et al., 2014). In addition, *the multiplicity and ambiguity* can be recognized as a part of information processing approach to task complexity (Campbell, 1988) Figure 9. Presents a schema of the complexities.

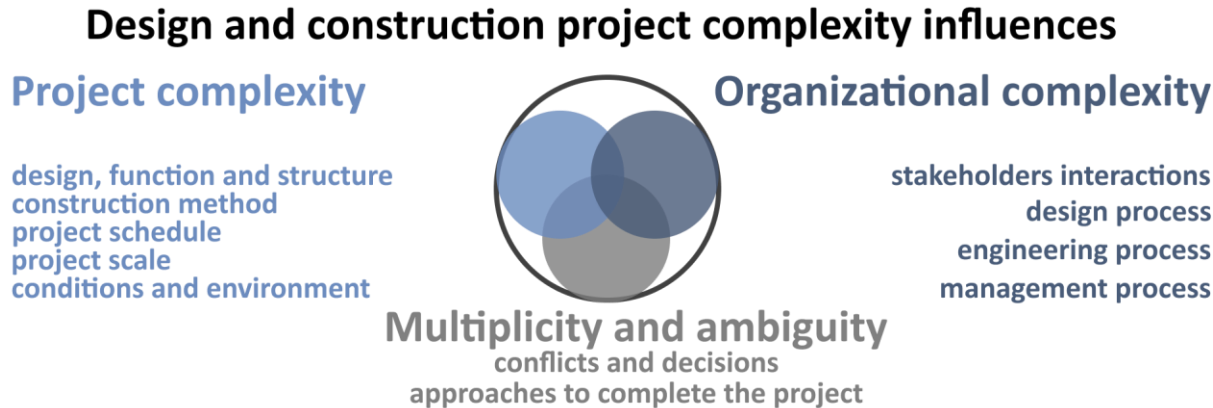


Figure 9 Schema of design and construction project complexity influences

Regarding the standards of interoperability, for example according to UK standards and classification, the complex digital models and collaborative BIM would correspond to *BIM maturity level 2* and prepare a transition to iBIM (integrated BIM) of level 3 (The British Standards Institution, 2014). Also, BIM development level grows through the design and construction phases, and they are followed by a *progressive complexity project and data increase*. Naturally, every project has its own features and

conditions, thus a *project documentation set* highly depends on a type of project, but also on a development phase and a level of detail.

Also, since the digitalization of practices in AEC, the collaborative use of BIM increases productivity and reduces design mistakes (Miettinen and Paavola, 2014). A greater productivity on a project is also achieved through implementation of open interoperability for BIM, since it assists with a flow of design, cost, construction administration, production and maintenance information (Laakso and Kiviniemi, 2012). Yet, also for BIM-based collaboration there is a *need for development of an effective project team*, which reveal organizational, technical, and other issues (Eastman et al., 2011). But specific to a project team is almost always temporary, and has specific tasks and responsibilities (Kubicki, 2006), these factors do not foster stakeholders to integrate completely into the BIM collaboration process and network. Since the context of AEC project delivery is quite complex, it might be challenging for project team to maintain optimal efficiency (Poirier et al., 2016).

Still, every project team faces challenges regarding the data complexity management. Thus, there is a *need for an efficient approach to represent and manage the project information* (Penttilä, 2006). BIM-oriented work methods and management highlight an importance of collaborative practices (Botton et al., 2011a). Every *professional on the team should adapt their workflow* and ways of cooperation on a project to the digital tools and BIM. Yet, digitalization of current practices aims to simplify the work methods and to improve the quality of the project. But as with any innovation, this takes time before complete integration into professional practices after modern technology appropriation period.

As BIM “... becomes a customized and integrated ICT rather than a simple simulation technology”, it assists project management with collaboration organization and fosters more integrated approaches to project delivery (Chan et al., 2018). BIM-based project management must address a variety of required transformations regarding tools (technology) and work processes to *optimize interoperability, software, modeling, visualization, and exchanges* within a specific AEC project. In addition, institutional environment and industry wide standardization also require transformations to provide a structure supporting efficient collaborative work (Chan et al., 2018).

The *complexity of project information and BIM* model development *also engages close collaboration* at the design and construction team. On another side BIM brings to the project team *benefit from improvement in the coordination and collaboration*.

Research approaches and frameworks of BIM collaboration studies

BIM implementation naturally depends on information systems and on institutional organization (Chan et al., 2018). Thus, the implementation of BIM often requires from a company and from project *managers to adjust the established workflows and practices*, to change coordination and collaboration methods in order to proceed with BIM (Poirier et al., 2016), to implement new frameworks or policies. In AEC, collaboration between disciplines and different organizations requires to take into consideration what is best for the project coordination and for the design (Homayouni et al., 2010).

In addition, a construction project information is often complex, therefore its accessibility or a possibility for project team to interact with the data is furthermore challenging. Thus, interactivity and interoperability of information and well-adapted digital supports become essential to foster project team efficiency in design and decision-making.

Therefore, following the development of BIM and of the need for efficient collaboration, different studies proposed multiple frameworks to outline and to structure BIM-based workflows and tools. Some studies focus on BIM collaboration outline in general, other investigate a chosen particular scope of

collaboration, either for design or for decision-making (value engineering), as well as the distant or co-located collaboration. Below, we propose an overview of the studies and their key elements related to our subject.

Before the establishment of BIM, the Virtual Design and Construction (VDC) project delivery approach was proposed by CIFE research center from Stanford University, which defines the virtual (digital) design, and puts digital models and simulations at the core of decision-making. VDC also allows project teams to resolve various project issues in virtual environment before the issue occurs at the construction site. Thus, it puts 3D and 4D models, as well as the processes and organization management into a coherent system. Fischer and Kunz describe VDC as “... *an integrating theoretical framework to predict engineering behaviors, and systematically manage projects and the business using the predictions and observed data, to achieve measurable business objectives.*” (Fischer and Kunz, 2004). This early work takes a perspective where research study Product, Organization and People models use at the use-case project for multidisciplinary collaboration and efficient decision-making.

Dossick and Neff report on a series of studies where they investigate BIM-based collaboration and its barriers, and they outline *that collaboration efficiency is reduced when:*

- *project stakeholders do not come from the same organization,*
- *do not have equal access to project information and BIM,*
- *participation in decision-making weight is not mutual (Dossick and Neff, 2009).*

Thus, a potential of enhancing efficiency lies in optimization of the access and democratic participation context. However, the same study *outlines an importance of a good leadership* to inspire project participants and to foster them to focus more on common goals of the project (Dossick and Neff, 2009). This leadership applies not only to the importance of design and construction competencies but also to the management competences, which become more critical.

Further, in the same line of studies, Homayouni et al., observe collaboration of integrated BIM design process and its *collaborative project environment* (CPE) (with or without shared technology adoption) on interorganizational level (Homayouni et al., 2010). The study outlines that BIM, as a technology dimension, and collaborative project environment as a social dimension are inter-dependable. Thus, Homayouni et al., propose *a theoretical framework to describe collaboration*, and to enhance it through the categories:

- *organizational: fostering integrated teams,*
- *technological: creating tools and strategies to encourage clear communication,*
- *social: developing transparent technology use.*

According to the presented in the study analysis a successful collaboration in one category reinforces the other categories as well. The authors also suggest to implement two types of strategies, which are necessary for successful collaboration: *teamwork and interorganizational meetings* (Homayouni et al., 2010). This suggestion presents the researchers and professionals with tools to better organize and thus enhance the collaboration efficiency.

In another series of studies, London et al., proposed a *BIM decision support framework* to assist AEC professionals with the choice of BIM uses, which *encompassed work road-maps to manage BIM and to manage design, tools-activity matrix* (London et al., 2008), considering the importance of efficient management and clear description of protocols and roles, however, the study was conducted during the early time of BIM adoption when collaboration was still mostly relying on 2D documents exchanges.

Further, the work by Gu and London emphasizes that different factors foster the BIM adoption by AEC professionals, such as shifts towards more sustainable design and construction, facility management based on digital model and *need to support more inclusive multidisciplinary collaboration* (Gu and London, 2010), which enhances the previously mentioned barriers. The research outlines requirements from a perspective studying *process, product, and people* categories. At a *process category* “integrated model development needs greater collaboration and communication across disciplines”, at *product category* “expectations are different for different users” since designers, contractors and managers see and use BIM tools in different ways regarding their activities and needs, and at the *people category* “new roles and relationships within the project teams are emerging”, such as BIM managers, coordinators, VDC experts, etc., which highlights the change of dynamics in collaboration and need for new skills (Gu and London, 2010). Thus, to overcome these issues, Gu and London propose *a custom collaborative BIM decision framework implementation*, which offers to:

- *provide the actors with the understanding and implementations of BIM technologies,*
- *create awareness about BIM uses and changes,*
- *generate a reflective practice among industry players (Gu and London, 2010).*

The proposed framework aims for collaborative design and for an organization that enhances links among process, people, and product, but in a scope of our study the proposal lacks focus on technology place in the system, as well as the innovative construction and management approaches.

Another study of BIM-based multidisciplinary collaboration by Singh et al., focused on a BIM-server as a distant synchronous collaboration platform for distributed design, and it outlines that groupware implementation may be challenging due to users *lack of experience with multidisciplinary digitally enhanced collaboration*, or due to the difference of roles or to the conflicting goals (Singh et al., 2011). The study investigates the subject studying *processes, tools and people categories*, and suggests that collaboration requirements and thus technology *vary from project to project*, which influences BIM-server setting and use (Singh et al., 2011). The study describes that the framework of technical requirements for a BIM-server must include:

- *BIM model management-related requirements: BIM model organization, Model access and usability, User interface,*
- *design review-related requirements,*
- *data security-related requirements,*
- *BIM-server set-up, implementation and usage assisting requirements.*

The proposed framework not only considers BIM requirements, but also point out the *importance of quality interactions* (humans with computers and with each other), presents a comprehensive perspective on collaboration understanding, however the proposed framework is limited to BIM-server technology, and on distant and not co-located collaboration.

Kassem et al., investigate the implementation of BIM and Collaborative Design Processes, and overview existing descriptive and prescriptive frameworks. They also outline *distinction of frameworks from protocols*, which are present on an industry-wide level, yet which still must be adapted to every project particular features and provide guidance for implementation (Kassem et al., 2014). Thus, the research *proposes protocols for BIM collaborative design* that include:

- *methodology,*
- *interactions between technology, process and policy fields, and key feasibility decision points,*
- *flowcharts and diagrams with increasing level of details (Kassem et al., 2014).*

This approach highlights an importance of not only technology considerations but also of the processes and organization (categories). In particular, they emphasize the *importance of a shared vision of project delivery* processes for efficient collaboration, and an influence of BIM on quality of information and deliverables to involved stakeholders (Kassem et al., 2014). The proposed description of BIM collaborative protocols, despite being very comprehensive, highlighting stockholders' roles, BIM tools, is rather focused on design support, and not on decision-making. However, the study also, reports on two use-cases with *design coordination and 4D planning, and highlights the roles*, where 4D planning is a responsibility of a contractor, and relies upon inputs from architect, structural engineer, MEP engineer and client (Kassem et al., 2014).

Poirier et al., also investigated upon the subject of collaboration in AEC, and proposed a conceptual framework (meta-framework) for Collaborative Project Delivery Systems, which is taking into account *process, technology and organization* categories but also introduces *the context dimension*, which encompasses these categories, and “*defines the environment in which evolves the collaborative project delivery system*” (Poirier et al., 2014). The framework also analyzes *interoperability construct across these dimensions (categories)* (see Figure 10), expanding beyond technological interoperability towards process and integration unlike other frameworks (Poirier et al., 2014). This approach is more comprehensive, and the notion of context presents an advantageous way to outline the project particular requirements.

An empirical study within Chinese AEC industry context by Liu et al., investigates BIM-based multidisciplinary collaborative design and construction with AEC professionals focus groups and interviews, and conducts their *analysis from a socio-technical perspective*. The study proposes a taxonomy of concepts that influence BIM successful collaboration through dimensions of issues related to:

- *technology: IT capacity, technology management,*
- *people: attitude and behavior, role-taking,*
- *processes: trust, communication, leadership, learning and experience (Liu et al., 2017).*

Authors summarize these concepts and categories relations with a *Model of BIM collaboration effects* (Figure 11) (Liu et al., 2017). The proposed perspective outlines the place of the dimensions, yet *does not include learning and experience* into the relations of BIM collaboration, however, from Lean construction perspective they are a part of the project delivery process for every decision-making

Moreover, the study stresses that despite efficiency improvement benefit of BIM's implementation on enhanced collaboration, it also presents project teams with *organizational challenges which nevertheless may limit the collaboration efficiency*. Thus, the study emphasizes a need for *balance between these technical and social concepts* to ensure efficient functioning from design and construction (Liu et al., 2017). Furthermore, Liu et al., emphasize *a need for new types of collaboration for BIM-based projects* with more integrated approaches, therefore, they *outline a potential in use of IPD to foster trust and communication, and to structure legal and organizational aspects of project delivery* (Liu et al., 2017). The study focused on more general aspects of BIM-based collaboration without particular perspective on collaborative decision-making or nD BIM uses, yet it presents a vision encompassing socio-technical approach and people, processes and technology issues.

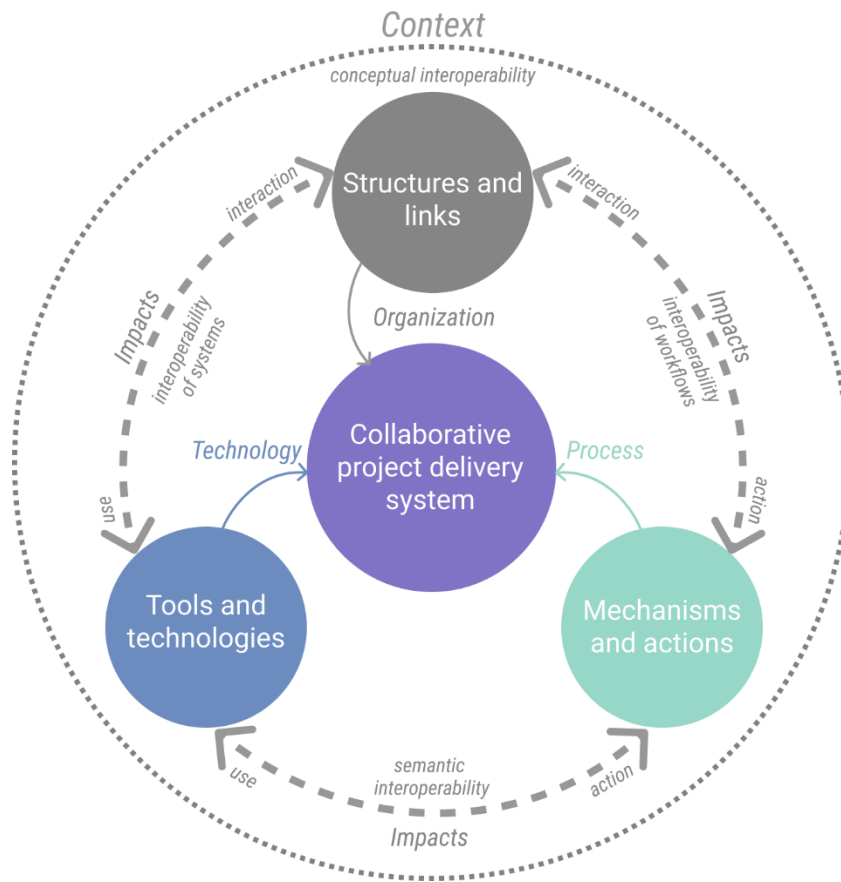


Figure 10 Collaborative Project Delivery Systems – A Conceptual Framework (adapted from(Poirier et al., 2014)

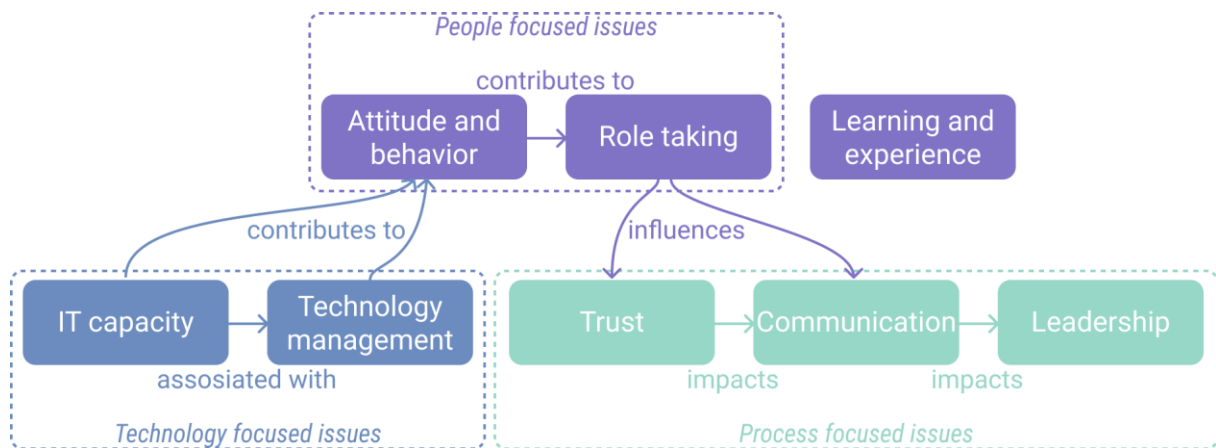


Figure 11 Model of BIM collaboration effects (adapted from (Liu et al., 2017))

Table 3 presents a summary of the discussed studies. With the development and adoption of BIM and other innovative approaches to design, construction and management, the research frameworks tend to investigate in depth various aspects in comparison to more general approaches. The technical and social perspectives are recurrent topics in the research approaches, highlighting a distinction technology related problem, from processes, people, organization. The studies also seek to structure collaboration on various levels either on interorganizational or on individual, however they do not study a group of professionals as an entity making decisions with BIM supports.

Table 3 Summary of studies of digital and BIM collaboration

| | Approach | Methods | Collaboration | | | | | Technology and HCI | Findings |
|-------------------------------|---|--|---------------|-----------|---------|----------|------------|---|--|
| | | | Scope | Location | | Supports | | | |
| | | | Design | Decisions | Distant | | Co-located | | |
| Fischer and Kunz, 2004 | VDC Product Organization Process | Use-cases | ● | ● | - | ● | 3D 4D | iRoom multi-user multi-display | 3D and 4D models help to improve coordination in all life cycle phases. Digital tools use in AEC fosters efficiency, yet reveals needs to manage various complex issues: technical, environmental, social, legal, cultural, etc. |
| Homayouni et al., 2010 | Theoretical framework of collaborative project environments and interorganizational BIM Social, Organizational Technological | Grounded theory; Ethnographic observations; Interviews | ● | ● | ● | ● | BIM | - | Strategies to support integrated BIM team collaboration: teamwork; interorganizational meetings. Theoretical categories: fostering integrated teams; implementing tools and strategies to encourage clear communication; developing transparent technology use |
| Gu, London, 2010 | Collaborative BIM decision framework Process, Product, People | Focus group interviews | ● | - | ● | - | BIM | - | Managing design process roadmap: opting activities; purpose and phase matrix; non-technical requirements Identified needs to: Provide the actors with the understanding and implementations of BIM technologies. create awareness about BIM uses and changes. generate a reflective practice among industry companies |
| Singh et al., 2011 | Framework of technical requirements for a BIM-server Process, Tools, People | Focus group interviews, Case studies | ● | - | ● | - | BIM | Single user approach, with specialized views for every discipline | Digitally enhanced collaboration requirements: BIM model organization, Model access and usability, UI. Design review-related requirements. Data security-related requirements. BIM-server set-up, implementation and usage assisting requirements; |
| Kassem et al., 2014 | Protocols for BIM collaborative design Process, Technology, Policy | Grounded research Case studies | ● | - | ● | ● | BIM 4D | - | Interactions between elements of the policy, process, and technology field. Technology diagram for BIM protocols; BIM workstreams and stakeholder involvement. Design coordination and 4D planning |
| Poirier et al., 2014 | Meta-framework Process, Technology, Organization Context | Systematic literature review | - | - | - | - | BIM | - | Conceptual framework and dimensions of interoperability. Introduces the context dimension |
| Liu et al., 2017 | Model of BIM collaboration effects Process, Technology, Organization | Socio-technical theory Focus group interviews | ● | ● | ● | - | BIM | - | Identified a need: For balance between these technical and social concepts. IPD use to foster trust and communication, to structure legal, organizational aspects of project delivery |

Key points of 1.2.1

Collaboration and BIM

- Design and construction of a project require participation of various AEC professional representing different disciplines and working together, which is beneficial to the project, yet presents various challenges due to the different focus of each discipline, to the usual tools and methods. These ways of working together like networking, communication, cooperation, and collaboration correspond to a higher level of interactions and shared tools, goals, responsibility.
- Collaboration has a variety of definitions, presenting different perspectives on the subject. In our study we refer to collaboration as to a dynamic and evolving with project cycle activity of project aiming to deliver the project in the most efficient, integrated and quality focused way, and executed by the project team members, who share mutual goals, resources, project information, benefits, and risks, in a specific context shaped by project requirements, tools, people and processes.
- Collaboration focused on project design has been enhanced by the development and adoption of BIM tools and protocols. It puts technology like nD models and information management in the core of a socio-technical system, and is encompassed by synchronous collaboration, coordinated work practices and institutional and cultural framework. However, within the same system, project team members interact not only for design but also for project construction and management, and they require relevant BIM tools for collaborative decision-making.

1.2.2 Lean construction and Integrated Project Delivery approaches

More collaborative and integrated project delivery methods emerge with development of management and engineering science. A project delivery method not only creates legal frame for a project team, but also provides context and tools for team collaboration. Therefore, the subsection emphasizes Lean construction principles and collaboration relation (1.2.2.1). In addition, the following subsection outlines IPD concepts and then overviews their role for establishing collaboration context (1.2.2.3).

1.2.2.1 Lean construction and collaboration

Towards Lean in construction

From a broad perspective of research influences and connections, the BIM research and establishment is strongly related to the advancements in domains of computer science, digital modeling, and human-computer interactions, whereas the Lean construction is naturally related to advancements in project management and in production management domains.

In early stage of Lean construction theoretical bases establishment, Howell (1999) presents a history of **Lean production** and describes it as “... a new way to design and make things differentiated from mass and craft forms of production by the objectives and techniques applied on the shop floor, in design and along supply chains.” (Howell, 1999). Then, he describes that application of this new form of management to AEC results in Lean construction.

To set clear theoretical basis, Koskela analyzes production and presents the **Transformation, Flow and Value (TFV) theory** of production and identifies three models of production in construction:

- *Transformation: transformers production into the product, with the focus on efficiency, using tasks management and WBS,*
- *Flow: manages a flow of material through the production, with the focus on waste elimination, using pull production and continuous improvement,*
- *Value generation: understands and delivers upon the customers' needs, with focus on elimination on value loss (Koskela, 2000).*

Thus, the transformation is in a way a reflection of conventional production system and methods similar to CPM, in the flow model the time is added as an attribute, and **pull planning takes into consideration the flow and the value**. Koskela suggests that a combination of these models would be the most beneficial (Koskela, 2000). These studies become a part of the theoretical basis of Lean construction, which would focus on the project optimization as a system, and not on individual parts of the project optimization. Further, Dave (2013) refers to the TFV framework as a fundamental from lean perspective and addresses it while prototyping VisiLean system (Dave, 2013), (see 2.2.1.2).

Even though the direct and practical reference for Lean construction concepts inspiration is Lean Production Theory (LPT) developed by the Toyota Motor Company in Japan, Koskela et al., (2019) study the origins of Lean construction from the perspective of sciences of engineering development, and outline that the theoretical origins come from the scientific method, based on Shewhart's quality control management studies and **plan-do-check-act cycle** (PDCA), which was further taught by Deming to Japanese managers in the 1950s and contributed to the Toyota way: “... the PDCA cycle, which had

become ingrained in the company culture to such an extent that it had become tacit knowledge.” (Koskela et al., 2019).

Koskela et al., observed despite the extensive number of studies on lean principles, the theories underlying lean production do not seem to be commonly known, thus they study the epistemological meaning of Lean and Traditional construction. The study investigates the fundamentals and outlines the *pre dominance of Platonic epistemology in AEC* and management, which considers the ideas about the world true and relies on deduction, which reflects in *use of CPM* as a main scheduling and managing tool, without taking into consideration the need to learn and adapt from the real world (Koskela et al., 2019). The study's analysis states that *Lean construction* was rather influenced by *Aristotelian epistemology* which is using deduction, induction and abduction, thus *learning from the empirical reality* (Koskela et al., 2019). The proposed perspective establishes a firm basis and provides a deep understanding of the Lean construction origins.

Li et al., review literature on Lean construction from 1997 to 2016, and observe the significant growth of the topic and its *clear establishment and continuous development since 2006*, with the studies from the USA and UK being most present in LC research (Li, Li, et al., 2019), while France and Luxembourg present relatively small input to the topic. Lean construction is still evolving and needs to be adapted to every local context (Al Balkhy et al., 2021). Observations from an experience of BIM and Lean joint adoption and implementation in a company outline that the implementation into regular practices of takes time, with *Lean Construction taking longer to become a part of common practices than BIM* (Sacks, Korb, et al., 2017)

Like many innovations Lean construction emerged as a response to the actual issues. It was inspired by industry and grew with research and pilot projects to become a part of the AEC practices today. In summary, Lean construction approach provides a unique perspective on construction processes, activities, and resources management, shifting from the traditional delivery and production methods. Lean also shares the basis with the production industry and empirical approaches but has the origins set by engineering and research sciences.

Lean concepts outline

A variety of works on Lean topic often evoke such terms as *Lean thinking, production, process, approach, planning, tools, methods*, which could become a source of ambiguity.

Koskela stresses out the *difference between Lean construction and Lean thinking*, the last one does not represent a framework but rather a set of rules and business principles (Koskela, 2004). *Lean production and Lean construction* share common elements, yet they have a different focus either on product or on process. Defining *the Lean Project Delivery Process* Khanzode et al., (2006) states that it is *“... based on the principles of applying the theory of Lean Production to construction projects.”* (Khanzode et al., 2006), and originates from the works of Lean Construction Institute.

Howell highlights that *Lean approach* aims *“... to assure we do not contribute to variation in work flow and to decouple when we cannot get it under control.”* (Howell, 1999), putting at the focus the control of unnecessary variation. Seymour, (2013) argues that *Lean construction “... is a discipline that adopts the scientific attitude, as is appropriate (e.g., using statistics or strictly engineering terminology to communicate functional requirements), but it also recognizes the inevitable limitations of such formal or specialist languages.”* (Seymour, 2013). Such outline considers the roots of Lean construction and considers its methods as a part of term definition.

Further, Tommelein describes *Lean as a philosophy, and Lean construction as a shift of a paradigm* which “... adopts the “lean thinking” mindset” (Tommelein, 2015). Therefore, despite the variety of related concepts referring to the core ideas, each term outlines a specific Lean feature, but may be summarized as a philosophy.

Ballard et al., explain that *Lean construction “embodies a philosophy of production management”* which is contrary to mass production is applied rather to “one-of-a-kind custom prototypes.” (Ballard et al., 2007), since every project is unique. Further, Sacks, Koskela, et al., (2010) emphasize that “*Lean construction refers to the application and adaptation of the underlying concepts and principles of the Toyota Production System (TPS) to construction.*” (Sacks, Koskela, et al., 2010). Koskela et al., (2019) emphasize that: “*Lean construction originated as a set of countermeasures to specific problems in construction, but has more recently evolved through the adoption and adaptation of methods and principles of lean production.*” (Koskela et al., 2019), which outlines the empirical and result focused nature of Lean.

Lean tools and processes aim to reduce nonvalue activities (Fischer et al., 2017; Ch.9). Dave et al., (2013) emphasize some of the Lean tools, such as Target value design (TVD), Value stream mapping (VSM), set-based design, choosing by advantage (CBA), *integrated lean project delivery (ILPD)*, Last Planner System®, A3 problem solving, *5S, Six Sigma, plan-do-check-adjust procedure, Andon boards*, etc. (Dave et al., 2013). Every tool provides specific benefits; however, our study focus is not on specifics of Lean construction implementation, but use of Lean as a one of the elements framing collaboration and to use its’ principles for more collaborative and integrated efficient decision-making at project meetings.

In summary, Lean construction presents AEC professionals with a philosophy, but also with an approach encompassing processes, methods, and tools to implement efficient waste controlling with the aim and value focused construction management. In addition, within Lean construction the “*Lean Construction planning and control techniques reduce waste by improving work flow reliability.*” (Ballard et al., 2007). The planning is a part of project time and resources management, and with the scope of our study on 4D strongly dependent on to time management, Lean construction planning and control are further implemented as key concepts for the prototyping.

Lean construction principles and collaboration

Lean construction may be characterized by: “*a clear set of objectives for the delivery process, aimed at maximizing performance for the customer at the project level, concurrent design of product and process, and the application of production control throughout the life of the product from design to delivery.*” (Howell, 1999). Thus, it sets a clear frame for the project and for the project team, creates a clear basis for the *common and collaborative development*, it also seeks to establish efficiency of design and construction, and to present a frame as well for project management and control.

In order to emphasize the philosophy and methods of Lean construction various interpretations exist, however the main principles remain constant. Sacks, Koskela, et al., emphasize the core principles of the Toyota Production System (TPS) applied to construction:

- *the reduction of waste,*
- *increase in value to the customer,*
- *continuous improvement (Sacks, Koskela, et al., 2010).*

The TPS principles create the core, which unites methods, tools, and processes of project development into a single frame. In addition to these principles, Lean construction has developed other

principles as well, which are particularly relevant to construction, to design integration and to process management.

The understanding of “waste” (“muda” in Japanese in the TPS) in Lean construction encompasses the inefficiency in production or physical waste, but also the process waste, which includes for example the waste of time or costs, and improvement of the value generation to the client. In Lean production Taiichi Ohno emphasizes the following categories of waste:

- *Waste of overproduction,*
- *Waste of time on hand (waiting), vacating,*
- *Waste in transportation,*
- *Waste of processing itself,*
- *Waste of stock on hand (inventory),*
- *Waste of movement,*
- *Waste of making defective products (Taiichi Ohno, 1988).*

Together with these categories, in Lean Construction there are also the wastes of *unevenness and unreasonableness*. In addition, in Lean Construction “*not value-adding work*” also represents a waste category, encompassing all the supporting activities which do not generate the value but are still essential and unavoidable (Sacks, Korb, et al., 2017). Therefore, due to the specifics of the AEC Industry, some principles were subject to adaptation for more relevant application, and others were identified by the AEC specific needs and recent digitalization.

Within the last thirty years, as much as with digital technologies and BIM community growth, the Lean research and practice community grew as well as a result from the efforts from various authors, and from Lean Construction Institute (LCI, since 1997), from the Annual Conference of the International Group for Lean Construction (IGLC, since 1993), from various workgroups and projects. The efforts have fostered the development of LC principles and their implementation, as well as their evolution.

For example, early in BIM establishment time British Standards Institution issued BS 1192:2007 guidelines for AEC assisting with BIM collaboration organization also emphasizes the need to avoid wasteful activities like:

- *waiting and searching for information,*
- *overproduction of information with no defined use,*
- *over-processing information, simply because the technology can,*
- *defects caused by poor coordination across the graphical and non-graphical dataset that require rework.*

Further, the British Standards Institution in PAS 1192-2:2013 assisting with collaborative project information production outlines the importance of understanding the *value from a client’s perspective and setting a balanced work flow*, and suggests to implement these Lean principles (wherever possible) to optimize the use of resources to produce the maximum value for the client (PAS 1192-2:2013, 2013). These standardization and legislation efforts were subject to trial by implementation and established basis for the international BS ISO 19650 in 2019. These efforts illustrate search for synergetic implementation and requirements for clear frameworks to do so.

Lichtig (2010) reports on use-case of Lean construction framework for a Sutter Health construction project, highlights that construction is not as repetitive as manufacturing, and use of LPS®, and reports that “*Early assessments of Lean Project Delivery support the conclusion that risks associated with time, cost, quality and safety issues can be reduced by implementing lean thinking.*” (Lichtig, 2010).

The Five Big Ideas were implemented to foster efficient Lean project delivery:

- *Collaborate, Really Collaborate,*
- *Network of Commitments,*
- *Tightly Couple Learning with Action,*
- *Optimize the Project, not the Pieces,*
- *Increase Relatedness. (Lichtig, 2010).*

Dave et al. also describes core functions of Lean construction as well, including the reduction of waste. They stress out that the reduction is possible “... by getting the quality right first time, through a better designed product, reducing the product variability, i.e. reduction of the need for changes during the later phases of design” (Dave et al., 2013). Therefore, the project team must be presented with the tools supporting efficient design, control, and decision-making. Another identified **core functions are “improved flow and reduced production uncertainty” and “reduction in overall construction time”** (Dave et al., 2013). Thus, in addition to waste reduction and reliability improvement, the efficient time management and processes are essential.

Fakhimi et al. outline that barriers for Lean construction adoption first come from that **lack of awareness or experience with correct implementation of lean** principles which influence the process issues. Second, there are barriers from the issues related to people, such as:

- *lack of top management commitment,*
- *governmental aspects,*
- *culture and attitudinal issues,*
- *the fear and resistance to change,*
- *educational issues,*
- *lack of training,*
- *lack of human skills and experience (Fakhimi et al., 2016).*

Not only the Lean concepts and principles, but also a framework would be necessary for successful implementation of Lean construction. The above-described Target Value Design and Last Planner System, as well as Lean Project Delivery System are designed to structure the implementation. The **Lean Project Delivery System (LPDS) is a project delivery method**, emerged in 2000 and updated since. Primarily it seeks to establish a lean production system for a design and construction project, to **establish a project definition process with project’s constraints (schedule, costs, location) and means to achieve client’s goals** (Ballard, 2008). As illustrates a conceptual representation in Figure 12, it consists of 5 phases: Project definition, Lean design, Lean supply, Lean assembly, Use, and of corresponding to the phase triads of modules which assure interconnections of the phases, as well as Production control and Work structuring modules present at every phase (Ballard, 2008).

Among other various aspects, LPDS emphasizes the role of design and construction professionals **to provide guidance to the project’s owner and users** in order to define in the most detailed and relevant way the values, uses, design criteria and requirements for the project (Ballard, 2008). Therefore, it places **the joint responsibility and work towards an outline of the goals** in a basis of decision-making process. Moreover, LPDS requires for a **collaborative use of a single digital model** of the project as a support for decision-making.

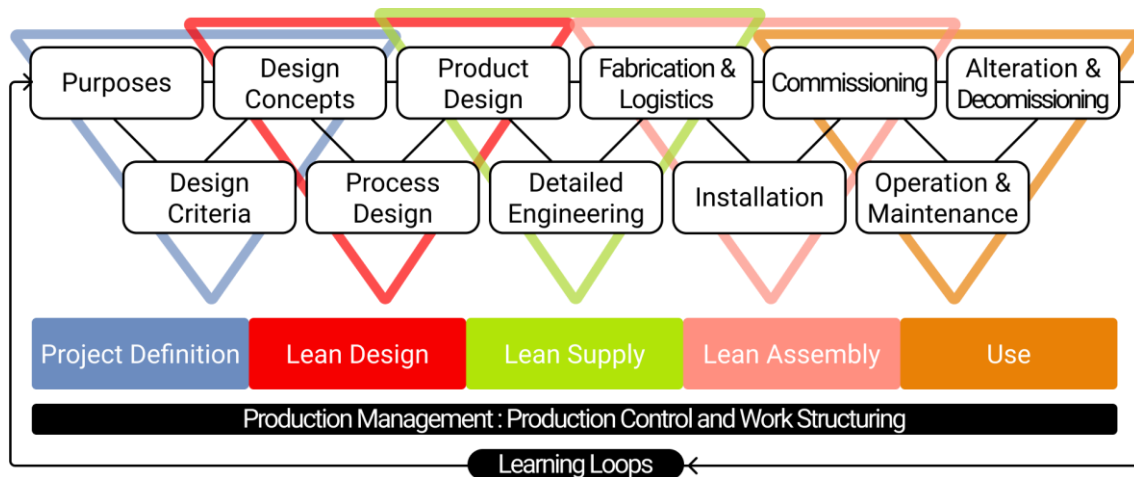


Figure 12 The lean project delivery system adapted from Ballard, 2008

1.2.2.2 Scheduling and Last Planner System

Collective scheduling

Ballard et al., outline that *stabilization of workflow through a reliable planning* is the primary concern of Lean construction (Ballard et al., 2007). The project, the budget and schedule, productivity and production are interdependent from decision-making perspective in any project (Ballard, 2000). Thus, it is important to create an adaptive system which incorporate all these concepts. One of the elements of the integrated information scheduling, *Pull planning* main aim is to improve the reliability of workflow on construction, but since it *engages the collaborative development of project schedule it "... builds a level of understanding and community"* (Fischer et al., 2017; Ch.13). Ballard and Tommelein explain the Pull planning as the process where *"...the first pass is done backwards from target completion to start. That is done in order to promote reliable promising among the participants who are working together in the project, phase, process, operation, or step being planned."* (Ballard and Tommelein, 2021).

In addition, Lean planning is only possible with efforts of foremen, and in order to be efficient, the management must assure that *"... production managers must also be sure that the right number of people with the right skills, experience, and training will be available when they are needed."* (Fischer et al., 2017; Ch.15). Therefore, it fosters closer collaboration and would require technology and process management support.

Fischer et al. compare the traditional scheduling to IPD and Lean scheduling, and suggest that to be efficient the entire project *team should share the responsibility of decision-making and planning*. With integrated planning the project milestones become team deliverables, therefore highlight the common goal. To assure such unity, the project management must arrange conditions to meet the master schedule, and on an execution level the foremen work jointly and coordinate using the Last Planner® System (LPS®) (Fischer et al., 2017; Ch.15). According to Michalski et al., the topic of *LPS® is one of the most commonly mentioned* in research from the last ten years (Michalski et al., 2022).

In observations presented by Ballard (2000) the *CPM did not assist with efficient weekly tasks planning*, resulting only in a half of them being executed as planned, thus Ballard describes the Last Planner® method to implement not only the "push" (traditional approach with production based on the

forecasts) but also the “pull” (demand-driven) planning (Ballard, 2000). In addition, by LPS® and BIM enhance stability and visibility in a project (Sacks, Korb, et al., 2017).

Last Planner® and schedule levels

“The Last Planner® production control system is a philosophy, rules and procedures, and a set of tools that facilitate the implementation of those procedures.” (Ballard, 2000). The system allows production unit control and work flow control. Ballard et al., (2007) describe *Last Planner® System which represents a planning system that implements lean construction*, and provide guidelines for LPS® use, and illustrate the planning elements of the system with the *Last Planner® planning cycle* (Figure 13), which comprises:

- Master schedule covering an entire project,
- Phase schedule emerging from collaborative planning,
- Lookahead schedule with constraints analysis,
- Weekly work plan with measured percent plan complete” (Ballard et al., 2007).

Learning also represents one of the elements of the cycle. These elements of the cycle represent various levels of detail for a project time management, and every level corresponds to particular purposes. Ballard et al., (2007) distinguish a *Frontend planning*, comprising Master scheduling and Phase scheduling, and *Production planning*, comprising Master scheduling and Phase scheduling, comprising Lookahead scheduling and Weekly work planning (Figure 13). Which corresponds to increase of level of detail of project information from Fronted to Production, and to project life cycle.

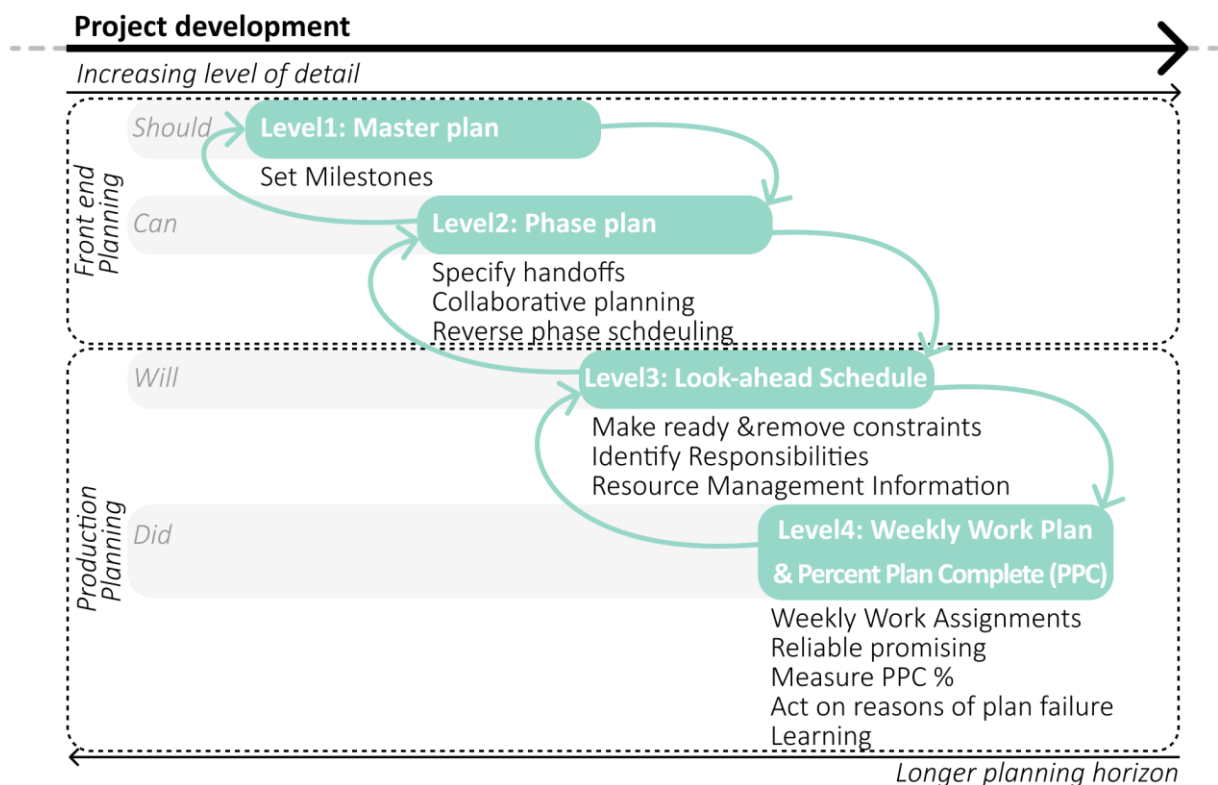


Figure 13 Last Planner® Planning Cycle adapted from (Ballard et al., 2007), Lean Construction Institute

According to the LPS® Front end planning, the project time management process starts with *the Master schedule* which “... initiates strategic planning, identifies major milestone dates and incorporates critical path method (CPM) logic to determine overall project duration.” (Ballard et al., 2007). Thus,

essentially it is used as “a coordinating map that pushes completions and deliveries onto a project” (Ballard et al., 2007), and corresponds to what “should” be done. Therefore, this first level of detail of a schedule establishes the basis for project goals, deliverables, and basis for strategic decision-making.

Fischer et al. describe, that a “**Master schedule milestones** establish the targets for the production scheduling. Working backward from delivery, the team defines major deliverables for construction, fabrication, and procurement, permits, and design.” (Fischer et al., 2017; Ch.15), at the moment of creation of the master schedule it is essential to consult all the project participants, highlights that it does not provide a granular level of planning, and it is a document that is flexible and evolves to follow construction scheduling (Fischer et al., 2017; Ch.15).

Next, the **Phase schedule** is “... a detailed schedule that evolves during the project by magnifying the master schedule into more detailed project components”, (Ballard et al., 2007), and corresponds to what “can” be done. Phase schedule is a **result of collaborative planning and reverse phase scheduling**, and it encompasses: activity durations, handoffs, relationships. Therefore, this second level of detail of a schedule continues to focus on project goals and deliverables but becomes the basis for strategic and tactical decision-making. In addition, Phase schedule is a result of collaborative activities occurring on pre-construction phase which are the primary scope of our study.

Further, The Production planning must establish a reliable and continuous flow process (CFP), first through the **Lookahead schedule**, which provides more details and adjusts budgets and schedules, assures the control of the production, is used as an element that links front end and production planning. It represents “... a list of activities that need to be worked on over the upcoming six weeks.” (Ballard et al., 2007). However, the window of 6 weeks may be shortened or extended according to the particular needs of the project or a planner. It corresponds to what “will” be done, thus represents actual commitments, surveyed by Last Planner®. The commitment planning “... involves committing to what will be done, after evaluating 'should' against 'can', based on actual receipt or resources and completion of prerequisites.” (Ballard et al., 2007). The Lookahead plan is updated weekly to account for constraints impacting the reliable workflow, identify responsibilities, make assignments ready, screen, analyze and pull resources. For example, the Last Planner® (supervisors) measures the assignments made ready (AMR) and assignments anticipated (AA). Thus, the decisions are based on real evaluations and constraints, and they result in Last Planner’s work plan. Therefore, this third level of detail of a schedule naturally maintains the focus on project goals and deliverables, but closely scopes reliability. It becomes the basis for tactical and operational decision-making. In addition, Lookahead schedule is as well a result of collaborative activities occurring rather during early pre-construction and especially during construction phase.

Finally, the **Weekly work plan** “... is the most detailed plan in the system. It directly drives the production process.” (Ballard et al., 2007). And at this level the focus is on reliability, fostered “... by making only quality assignments and reliable promises so that the production unit will be shielded from upstream uncertainty.”, where a **work assignment** refers to “... a detailed measurable commitment of completion.” (Ballard et al., 2007). In addition, the Weekly work plan is used not only for planning and for management, but also for Percent of Plan Complete (PPC) measurements, which allow to analyze and learn from the failures, thus it corresponds to what the teams already “did” (Ballard et al., 2007). Construction supervision and Last Planners maintain daily meetings to support the efficient workflow, and they support the reliability at the crew level. As outline Fischer et al. : “Safe, high-quality, and timely execution of work is only possible by planning production each and every day.” (Fischer et al., 2017; Ch.15). Therefore, this fourth level of detail of a schedule continues to aim at project goals and deliverables, but closely scopes reliability, but becomes the basis for tactical and operational decision-

making. In addition, weekly work plan occurs during construction phase which is not in a primary scope of our study.

All the presented elements (levels) of the planning cycle represent various levels of detail of a project schedule, various aims, and roles of team members. Thus, it presents not only the frame for process management, but also for organizational and technological management as well. It creates a context for relevant information to be visualized and managed at the relevant time, at relevant collaboration session. The collaboration protocols and digital tools must provide necessary elements to support these uses.

In addition to the Last Planner® planning cycle, *Work structuring, screening and shielding* are the activities of Lean Project Delivery System. Ballard et al., describe the *Work structuring* as a “... *production system design comprising development of operation and process design in alignment with: product design, structure of supply chains, allocation of resources, and design-for-assembly efforts with the goal of making work flow more reliable and quick while delivering value to the customer.*” (Ballard et al., 2007). Work structuring represents one of the key tools, and it manages “various levels of detail” from global to operations, as well as materials and information, unlike the traditional management with work packages.

Therefore, it is important *to assure the easy access to project information to support the workflow with data flow*. As highlighted by (Fischer et al., 2017; Ch.15) the project team must have access to all the information, like: “... *up-to-date design documents from the architectural and engineering drawings, building information models, fabrication and shop drawings, clear quality and completion criteria, and installation instructions.*” (Fischer et al., 2017; Ch.15).

In addition, in particular during product planning the Screening and Shielding activities become the tools of management. *Screening* is applied to Lookahead schedule and is described as “... *determining the status of tasks in the lookahead window for readiness relative to their constraints, then choosing to advance them into the lookahead schedule or retard tasks on the master schedule based on their constraint status and the probability of removing constraints prior to the task's scheduled start.*” (Ballard et al., 2007). Therefore, an access and easy updates upon the task status, are curtail for decision-making *Shielding* is applied to Weekly Work plan, and described as: “*Not releasing work to production units because it does not meet quality criteria, the work is not a quality assignment.*”, with an aim to “... *make production units less subject to uncertainty and variation, thereby providing them with greater opportunity to be reliable.*” (Ballard et al., 2007).

Thus, these activities are essential for LPS®, and they must be supported by collaboration protocols and by project team members, as well as by the digital collaboration tools. However, the levels of schedule detail present the primary interest of our study.

1.2.2.3 IPD and collaboration

Towards collaborative and integrated project delivery methods

Design and construction conclude with results due to collective efforts of various AEC professionals. Naturally, they need to collaborate and to manage the collaboration, and to assure an efficient project delivery. According to the study of Engebø et al., often a term referring to *the means of transforming the client's objectives into the final product* sometimes varies from “Project Delivery Strategy/Method/System” to “Project Procurement System/Method”, or “Construction Contracting

System/Method”, in addition there is no uniform approach for comparison of these practices (Engebø et al., 2020), for the sake of simplicity we continue to use the Project Delivery Method term.

A study by Ahmed and El-Sayegh reviews project delivery methods and suggest that the currently emerging methods correspond to the Project Delivery methods 4.0, as a parallel with Construction 4.0, since they are more collaborative citing *Alliances, Partnerships, Lean and Integrated Project Delivery (IPD)* (Ahmed and El-Sayegh, 2021). Another study by Engebø et al., describes recent developments and a tendency to shift from traditional methods like *Design-Bid-Build or Cost reimbursable* to emerging methods which are more collaborative and emphasize integrated design and delivery. Engebø et al., report that the shift is perceived as not easy, due to ***the need for contractual, organizational and social changes*** (Engebø et al., 2020) and propose to distinguish the methods that focus on:

- **support of integrated design and processes:**
- Design & Construction,
- Integrated Supply Chain Management (SCM),
- Management Contracting,
- Joint Venture consortia,
- **support of integrated design and teams:**
- Project Partnering,
- Project Alliancing,
- Early Contractor Involvement,
- Framework agreements,
- Integrated Project Delivery (Engebø et al., 2020).

Engebø et al., outline that inevitably the research is very dependent on the current state of AEC industry, with which it shares the context, for example, the studies reporting on IPD mostly come from USA (Kahvandi et al., 2017),(Engebø et al., 2020), or the studies on Alliancing report from UK and Australia (Fischer et al., 2017; Ch16),(Engebø et al., 2020).

Since, in our study we seek to investigate upon the need for more efficient management of digitally run projects, and the need for adapted to BIM projects delivery, as well as to propose a new co-located collaboration tool for 4D and Lean planning visualization at project team meetings, these collaborative and integrated methods become a part of the research context.

Integrated Project Delivery as collaboration study context

Earlier Mihic et al., perceived the IPD related reports as overly positive in literature (Mihic et al., 2014). An analysis of the feedback from project participants on IPD use-cases reports that the experience is rather positive compared to other (non-collaborative) project delivery methods (Cheng et al., 2016). Engebø et al., articulate that most of the research articles on IPD present description of the feedback on implementation experience, however not many studies propose a framework for analysis of the implementation (Engebø et al., 2020).

Poirier et al., investigated collaboration through innovative project delivery approaches, which bring shifts to the established practices and create new patterns, processes and roles (BIM managers, coordinators, IPD and Lean facilitators) (Poirier et al., 2016). From one perspective, innovative project delivery approaches of BIM, integrated design processes (IDP), IPD and Lean construction aim to facilitate and improve collaboration and value generation, “... by establishing stronger relationships and supporting more efficient and effective processes, by enabling and empowering agents to act and by offering artefacts that better support and are also better suited for use by agents within these structures

and processes.” and from another perspective, collaboration is itself a key to innovation (Poirier et al., 2016).

In addition, co-located collaboration sessions of design and construction team become a common element of complex IPD projects (Eastman et al., 2011), where they are seen as *“The main mechanisms to ensure that project teams carry out integrated processes are co-location and collaboration...”* (Fischer et al., 2017, Ch.7).

From more general perspective, the IPD framework considers a building as a result of assembly of various components from the integrated systems, which are assembled through the integrated processes, the project team is brought together through an integrated organization and relies on integrated information (Fischer et al., 2017; Ch.3). Thus, similarly to the socio-technical system of BIM, the information and digital tools are in the core of the framework, and it is encompassed by the organization and processes which would correspond to the social parts, in particular: *“Collaboration and co-location are the primary methods with which the integrated organization integrates the processes and carries them out efficiently”* (Fischer et al., 2017; Ch.3).

Therefore, *we use Integrated Project Delivery (IPD) as an example of an integrated, more collaborative, and lean related method of project delivery*, which would present our studies with a more global context of project delivery, exceeding beyond the particular scope of the project meetings.

According to the AIA^v *“Integrated Project Delivery: A Guide”* definition IPD *“...is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.”* (AIA, 2007).

According to Eastman et al., IPD’s main scope is *to meet requirements and to ensure quality, reduce time and cost*, through creation of *a cohesive team and close, early and effective collaboration of owner design team and contractors* (Eastman et al., 2011). Alarcon et al., (2011) report on a case study that the construction project delivery with IPD was efficient on time and on budget (Alarcon et al., 2011).

Ashcraft also argues that, since *“IPD is a collaborative, trust-based delivery method”*, when implemented in a project, it demands an *early stockholders involvement and a creation of a work context of shared responsibility*, risks on project outcome by all project participants which builds more cohesive collaboration environment and aligns all the parties to the same objective (Ashcraft, 2012).

In order to assure the successful implementation of IPD, Ashcraft proposes an IPD framework, where *on a macro level he suggests to organize the contract terms and business structure, and on a micro level to organize the protocols and processes through work design, information design, and team design* (Ashcraft, 2012). Also, such a framework should: *“remove impediments, and stimulate, communication, collaboration and creativity, align participants to well understood and agreed objectives, encourage and reward behavior that increases project value”* (Ashcraft, 2012). *Even though, a project owner is primary beneficiary of IPD* (Eastman et al., 2011), *all the project team members benefit from a joint project control*, (Ashcraft, 2012). *IPD uses measurable value and simulation and visualization, as well as production management and collaboration and co-location*, as the methods to achieve the project goals (Fischer et al., 2017, Ch.3), these methods are aligned with our research scope investigating 4D simulations, quality visualization and co-located collaboration.

^v American Institute of Architects

Also, one of the challenges is that IPD approach needs to be adapted to local construction and governing contexts (Kahvandi et al., 2017), therefore in French AEC context IPD experience is less developed than in USA, however its principles still present project managers with a framework for more efficient project delivery. Nevertheless, the IPD as an example of a project delivery method helps us to describe the complexity of a design and construction project *not only through socio-technical lens, but through people - IPD, processes – Lean construction, and tools - BIM perspectives.*

IPD and co-located collaboration

The place of collaboration in IPD, is as well important as in BIM or Lean construction. BIM is often perceived from a use for design as a tool for distant collaboration, however it uses for collaboration is extends beyond design purposes towards construction, processes control and project management. Sacks, Koskela, et al., suggested that the joint implementation of IPD and VDC techniques create a platform for an integrated project management and collaboration, by creating a contractual basis and supporting efficient use of information (Sacks, Koskela, et al., 2010). They also *hypothesized that IPD approach is required to reach full potential of a construction process. Therefore, the IPD establishes a basis for intagration, digitlal tools implementation and enhanced collaboration.* A report by Fischer et al. on a use-case of IPD implementation for a Hospital project construction that co-location significantly increased both the informal and structured collaboration of the team members (Fischer et al., 2017, Ch.8).

However, despite the benefits, IPD alters the design process, since a project team would rely a lot during the design on BIM knowledge and skills (Eastman et al., 2011). Yet, transition to IPD *requires a mental shift regarding the common practices and delivery methods, as well as a need for adoption of new contracts* (Ashcraft, 2012). These needs are similar to the one necessary for successful BIM collaboration, thus digitally driven practices and collaborative delivery methods require a clear structure of the workflows and team responsibilities outline. Regarding synchronous co-located collaboration at the meetings a structure of the meeting and roles outline are crucial as well.

IPD defines *Co-location or The Big Room* as “... the collaborative execution of work by the key project team members in a single location” (Fischer et al., 2017; Ch.14), sees the co-located collaboration as a tool that “... improves communication, enhances creativity, and develops the personal relationships that collaboration requires.” (Fischer et al., 2017; Ch.14), it *is supported by the integrated information, structured by the integrated organization, and allows integrated processes to teams*, thus it is connected to every aspect of IPD. However, in IPD approach, it does not only concerns decision-making and coordination but the design activities as well. Sacks, Korb, et al., (2017) emphasize that BIM and co-located decision-making together *foster social cohesion*. For example, the use of BIM in the big room improves communication by *fading the strict distribution of roles and responsibilities*. Also, the quality of project design benefits from more collaborative and coherent design and multidisciplinary problem-solving (Sacks, Korb, et al., 2017).

Fischer et al. summarize various impacts of IPD implementation into project development. On the broad scale of design and construction project, IPD as a project delivery method *reinforces interactions and creativity of project team members*, and provides them with improved collective understanding of project values, goals, progress (Fischer et al., 2017; Ch.14). Therefore, it first of all unites project team and its focus with the frame for more integrated collaboration and shapes a holistic context for all kinds of collaboration. However, the co-located collaboration remains an important element of IPD. The benefits brought by implementation of IPD co-location for design and decision-making meetings include *improvements on more accurate communication based on discussions and feedback*, together with *less*

time required for decision-making. In addition, IPD fosters the use of various digital and analogue tools to support the workflows. For example a clear and accessible to all project team members *visualization of information is used as a tool that assists with project development improves project and location-based construction management*, as well as *digitally based collaboration, communication and co-located decision-making* (Fischer et al., 2017; Ch.14).

Furthermore, IPD reflects on team members and their interactions, roles, and responsibilities. As mentioned in previous section, the definitions of collaboration vary on perspectives of studies or of the scope, the IPD approach also sees the collaboration as “... *both an enabler and an emergent outcome.*” (Fischer et al., 2017; Ch.13). Inevitably, project team members become the actors in collaboration, with IPD, all project team members collaborate *as an integrated team*, which “... *operates as a virtual organization committed to the project, ... allocates resources and makes decisions guided by the core project values*” (Fischer et al., 2017; Ch.1). Thus, the collaboration as well as the co-located design and decision making are inevitably relying on the integrated project team (Fischer et al., 2017; Ch.9). The team is naturally composed of different individuals, but the focus is on collective knowledge, responsibilities, and values, as much as with our approach to application design and prototyping we focus on the development for a group and not for a single user-focused collaboration and interactions.

Fischer et al. suggest that *major decision-making should be supported by multidisciplinary collaborative sessions* with implementation of tools proposed by Integrated concurrent engineering (ICE) (Fischer et al., 2017; Ch.14). Regarding the roles and activities of project team members, with IPD *decision-making is shifted towards the first project phases*, where not only the Owner and Designer collaborate at the Conceptualization phase (Expanded Programming), but also the Design consultants, Constructors and Permit agencies are included into decision-making during this phase (AIA, 2007). With IPD project Owners are in the heart of the change and have to be “*engaged and committed, can draw the team into its vision*” (Fischer et al., 2017; Ch.2). The same shift is for the Trade constructors engagement phase, they are included at Criteria design phase, before Detailed design, Implementation documents, Agency coordination and Construction (AIA, 2007). Such a shift only fosters closer collaboration, and also aligns with the BIM management reinforced effort during design phases.

Fischer et al. *summarize that for efficient collaboration requirements from IPD perspective regarding the multidisciplinary team members:*

- *Respect for the knowledge and skills,*
- *Understanding of project goals and values,*
- *Deep level of trust and a sense of community (Fischer et al., 2017; Ch.13).*

These, requirements should be enhanced by the protocols and tools used by project team. The optimal requirements setting for IPD co-located collaboration suggest not only to use relevant technology support, but also *to create necessary and optimal physical layout conditions* and to start the collaboration early in the design phase (Fischer et al., 2017; Ch.14). In addition, the co-location requires lots of wall space since the *visual management is essential to communication and collaboration quality*, which we explored and remarked as well.

In summary, IPD emphasizes the importance of a truly integrated team and processes, focuses on common goals, and seeks to create an environment fostering easier interactions and collaboration. Therefore, it provides the optimal context for collaboration. The co-located collaboration continues to be a part of the context but is not only seen as a result of processes and tools combined, but emphasizes the skills and input of every team member, thus focuses not only on processes but on people as well. In

addition, integrated approach values visualization tools as support for collective and more democratic interactive decision-making.

Key points of 1.2.2

Lean construction and Integrated Project Delivery approaches

- Lean construction and principles have more than two decades of development and establishment history, and continue to evolve today. They are fostering changes to project delivery methods and tools but to the whole approach and philosophy behind it, by putting into the core of the setting waste reduction, continuous improvement and learning and focus on increasing value for the client.
- Among other tools, the use of Lean construction for a project relies on more efficient and collective scheduling, focused on improvement of reliability of construction flow, reduction of waste and pull planning. Where Last Planner System® represents one of the most cited tools to do so, providing a framework for project and processes management comprising four levels of detail of the schedule relevant to particular purpose and decision-making, comprising: master schedule, phase schedule, lookahead schedule, weekly work plan.
- More collaborative and integrated project delivery methods emerge with the evolution of AEC industry, much like BIM or Lean construction development. An integrated project delivery method establishes the legal and methodological framework which fosters share of responsibilities and supports early involvement of various stakeholders at the program or design phases, thus it provides an environment for more integrated, trusted, democratic collaboration. It establishes the organization of project workflows, and it also puts digital tools, like BIM or VDC, in the core of the socio-technical system.
- Integrated Project Delivery (IPD), represents a well-documented example of a collaborative and trust-based method aiming to meet project requirements, ensure quality, reduce time and cost. Much like Lean construction, IPD seeks to enhance project team collaboration which would assure more benefits and efficient results, and they been reported as benefitable and complementary to each other. We refer to IPD in our study to represent an importance of implementation of a collaborative and integrated project delivery method to support collaboration and BIM use, to depict the most holistic system. However, we do not focus on the particular elements of IPD implementation.

Summary of 1.2

Collaboration and BIM, Lean construction and IPD overview

- Multidisciplinary collaboration is one of the key elements of design and construction project work processes and delivery. In last decades, the implementation of BIM enhances digital collaborative design, development of intelligent project nD models and simulations. Such advancements propose a variety of uses and require development of novel and well-adapted tools. In addition, to manage the models, organize workflows and establish efficient collaboration a development of new protocols and BIM related skills are required as well.
- More collaborative and integrated project delivery and construction management methods have been emerging in parallel with technological advancements. Despite the focus on specific goals and processes, IPD and Lean construction consider collaboration essential to successful implementation of their respective tools and methods.
- The described concepts outline complexity of design and construction project collaboration and allow us to implement a research approach *considering social and technological aspects, as well as a description through the combination of ideas representing people - IPD, processes – Lean construction, and tools - BIM*. However, for an integrated project delivery approach BIM (or digital tools) would represent the core of all activities, therefore it is inevitable encompassed by the integration. In addition, BIM is not only limited to the technology, but also includes information and collaboration management, thus it is not strictly limited to the “tools.” Furthermore, Lean construction does not yet include technology as the necessary element for implementation, however it does not only concern processes but also requires the philosophy shift impacting processes and organization. Therefore, the synergy of these approaches establishes the context for collaboration and 4D BIM studies.

1.3 Towards synergy of BIM/4D, Lean construction and IPD

1.1



1.2



1.3

The previous sections depicted advancements and concepts key to our research, in order to outline the context encompassing: BIM, Lean Construction, Integrated Project Delivery. Despite each of their individual focus on different aspects, they each aim for particular goals, nevertheless, by extension they fundamentally aim to improve efficiency of design, construction, management and also of multidisciplinary collaboration. In addition, by being relatively recent innovations, they also foster changes to traditional AEC approaches.

The following section describes the bonds and interactions between these concepts, and it aims to establish the common context, by outlining the particular interactions of BIM with Lean construction and with IPD, and to focus on the particular scope of our study on 4D BIM collaborative use for decision-making.

First, BIM and Lean construction topics in literature and their interactions are outlined in subsection 1.3.1. Second, the interactions of BIM and integrated project delivery are outlined in 1.3.1.2. These sections provide an overview of more global context of BIM, which is inevitably a part of our study. Finally, the subsection 1.3.2 summarizes the interactions of BIM, Lean construction and IPD, with the emphasis on 4D implementation, benefits, and requirements in perspective of studying 4D-based collaboration.

1.3.1 BIM implementation with Lean construction, and with Integrated approaches

The following subsection first presents a summary of BIM and Lean construction interpretation in the literature, in order to highlight the main investigations areas and limited amount of research on the subject (1.3.1.1). Second, the subsection cites the key studies which establish the basis for research of BIM and Lean construction interactions, it also outlines certain BIM and Lean joint implementation benefits as well as it outlines several requirements for future more efficient interactions. Finally, it emphasizes BIM and integrated approaches interactions and influence on collaboration (1.3.1.2).

1.3.1.1 BIM integration with Lean approach

BIM and Lean construction topics in literature

An implementation of every innovation takes time and efforts, moreover a joint implementation of several novel approaches which are shifting the established paradigms, like BIM and Lean construction may prove challenging and complex. A review of the literature by Michalski et al. covering the last decade and examining 58 research papers, presents observations of the ***trend of interest augmentation for BIM and Lean interactions since 2016***, and outlines ***four main topics*** from the analyzed research on their ***implementation and utilization***:

- the benefits,
- the issues,
- the supporting instruments,
- potential future demand (Michalski et al., 2022).

Such distribution and scope of the topics are typical since they encompass the most fundamental aspects of understanding of a phenomenon. Yet, they also report that the joint implementation is rather a developing field of study. The studies, also provide the AEC professionals with necessary information for adoption and implementation, as well as indicate the research perspectives.

Andújar-Montoya et al. review the BIM and Lean construction interactions. They present from a literature analysis that despite the large amount of research on each subject individually which ***reports “scarcity” of works on their synergy*** (Andújar-Montoya et al., 2019). Also, the researchers report that the studies from the literature were covering ***mostly the design phase (50%)***, however the construction phase was the second most covered (39%) by the studies, and the ***case studies and theoretical studies had equal amount of representation***. Li et al. also suggest that there is a ***need of integration of BIM and Lean practices in the construction phase, and during the design as well*** which would promote more integrated implementation and empower the synergy (Li, Li, et al., 2019). Despite design phase presenting with broader cover in the literature, the construction phase is studied as well, yet there is a lack of reports on observations of the entire project development cycle, as a continuous and integrated process of development.

Furthermore, regarding Lean construction adoption and implementation, there also barriers within the companies and across the industry, which do not foster the adoption, and are very similar to the adoption and implementation of BIM barriers. Al Balkhy et al. present a study of Lean construction adoption in Jordan industry and report on perceived lack of support from the management, as well as lacking training or understanding of construction teams. In addition ***lack of commitment and transparency in collaboration of stakeholders*** (Al Balkhy et al., 2021).

However, despite the variety of methods and concepts, Lean construction (LC), like BIM, may be understood as its main tools. Much alike BIM is often rather associated with a 3D model and not with information management. Li et al. review the literature, and report that Lean construction and BIM topic is *strongly associated with visualization and information management*, thus further the research scope *needs “... to explore interactions between BIM and LC beyond visualization”* (Li, Li, et al., 2019).

Andújar-Montoya et al. emphasize that *“... the interaction BIM and Lean Construction is an area still little explored that can open future lines of research associated to Lean tools beyond the Last Planner® system, and other agile management systems”*. (Andújar-Montoya et al., 2019). Which suggests the need for further *exploration with a variety of focuses*, as well as potential need for further studies and development of new tools.

From the perspective of AEC professionals, BIM and Lean are often perceived as relevant approaches for large companies. Tezel et al. review the literature on their joint implementation, and they report the *deficiency of research and detailed investigations of joint implementation* in small and medium-sized enterprises. Therefore, there is a *need for more studies to build a deeper understanding of integrated implementation* encompassing technological, organizational and legal aspects (Tezel et al., 2020). Such study would be challenging due to complexity of the scope. However, with an integrated approach would provide more holistic understanding would be beneficial.

Like the efforts from various researchers to understand diffusion and adoption of BIM and to assess its maturity, several similar efforts were made for BIM and Lean integration. For example, Mollasalehi et al. review the existing maturity models for BIM and Lean individually, and propose an Integrated BIM and Lean Maturity Model named “IDEAL”, with 5 *levels of integration*:

- *Initial – no interaction of BIM and Lean,*
- *Defined – a basic awareness of benefits of integrated BIM and Lean,*
- *Enhanced – a good understanding of the interactions and potential benefits,*
- *Advanced Integrated – an advanced level of integration between BIM and Lean approaches,*
- *Long-term optimization – BIM and Lean fully integrated.*

Within the proposed model, *collaboration and LPS® are implemented at the Enhanced level*. The proposed model allows to assess the maturity of both approaches implemented together (Mollasalehi et al., 2018). The proposed levels of integration naturally share some features with BIM maturity assessments and offer essential evaluation marks. And even the basic not integrated levels could provide changes to work practices and flows, thus provide a beneficial impact. However, more detailed tools and guidelines would be necessary for more comprehensive outline and for efficient integration.

The abovementioned gaps and the outline of BIM and Lean construction synergy provide a valuable awareness of the current limitations. They, also highlight that there is still *a need to adapt lean techniques focused on process to project-based approach*, as well as *a need for the joint implementation framework* of BIM and Lean construction approaches (Michalski et al., 2022).

BIM and Lean interaction studies

One of the key studies by Sacks, Koskela, et al. establishes the basis for investigations of BIM functionalities and Lean principles interaction in AEC. The researchers identify four principal areas of application of a set of Lean principles related to flow processes, to value generation process, to problem solving and to developing partners, with a number of relevant Lean principles, as well as they list BIM functionalities (Figure 14, Figure 15) (Sacks, Koskela, et al., 2010).

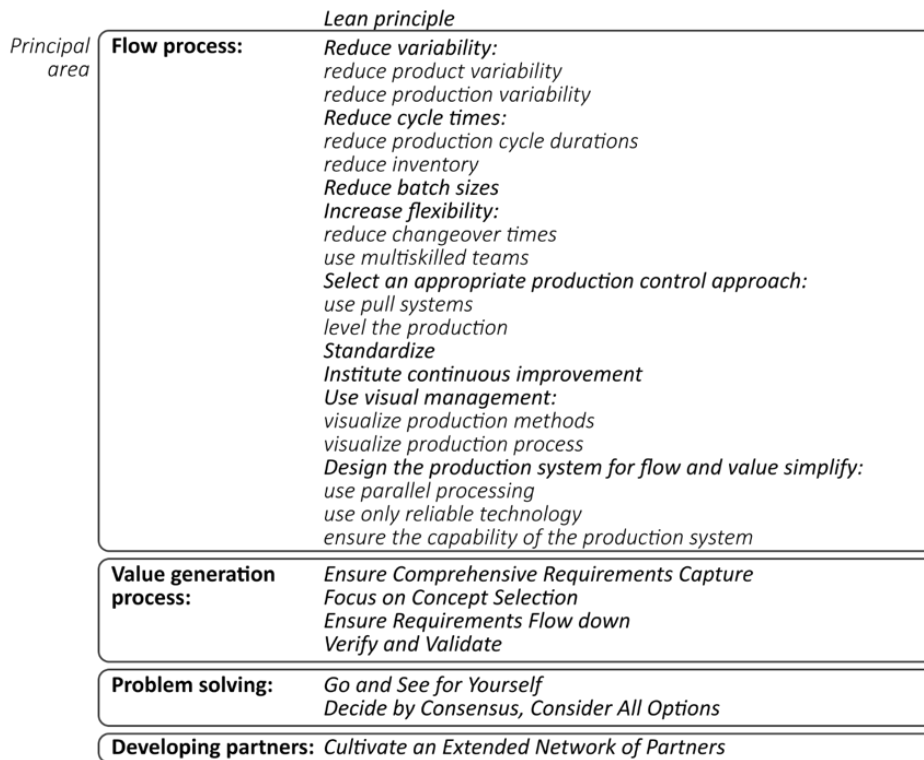


Figure 14 Lean principles (adapted from (Sacks, Koskela, et al., 2010))

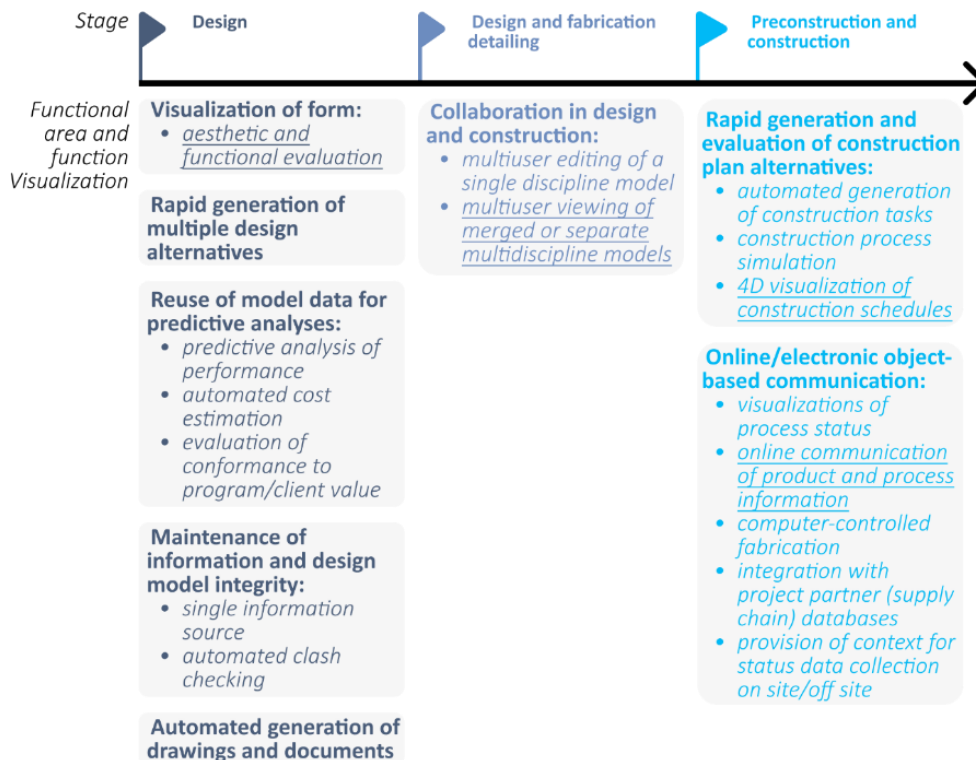


Figure 15 BIM functionalities listed by (Sacks, Koskela, et al., 2010) (adapted from (Sacks, Koskela, et al., 2010)), the underlined functionalities have more unique interactions with Lean principles

Further, Sacks, Koskela, et al. study each functionality in a set with each principle, and stress out that the interaction of BIM and Lean practices should be considered as a *complex whole process* (Sacks, Koskela, et al., 2010). Therefore, they highlight that both approaches may be adopted and implemented separately, however, during an implementation on a project *“BIM is expected to provide the foundation for some of the results that lean construction is expected to deliver”* (Sacks, Koskela, et al., 2010), and *BIM may become an enabler for lean transformations*. After listing the BIM functions and Lean principles Sacks, Koskela, et al. propose a *matrix that illustrates their interaction and synergy*. They outline that among the BIM functionalities those that have more of unique interactions are:

- *aesthetic and functional evaluation during design phase,*
- *multiuser viewing of merged or separate multidiscipline models during design and detailing phase,*
- *4D visualization of construction schedules during pre-construction and construction,*
- *online communication of product and process information pre-construction and construction.*

These listed functionalities are useful at various phases of project development, and assist with not only design activities, but they enhance collaborative decision-making and digital continuity of project data, as well as the use of 4D scheduling at pre-construction and construction phases, which correspond to the scope of our research.

Furthermore, according to the analysis, among the Lean principles those that have more of unique interactions:

- *get quality right the first time reduce product variability,*
- *focus on improving upstream flow variability, reduce production variability,*
- *reduce production cycle durations (Sacks, Koskela, et al., 2010).*

These listed principles with unique interactions must be enhanced with the protocols and tools. The outline of the principles suggests the room as well for optimal synergy of BIM and Lean construction. In the context of our study of collaboration and 4D use, such principles become requirements for new collaboration tools and scenarios development.

Following the research on BIM and Lean interactions, Dave et al. proposed a guide on “Implementing Lean in construction” regarding joint application of Lean and BIM, and summarize that *BIM contributes to Lean goals and fosters processes, as well as Lean processes also facilitate the adoption and use of BIM*. They outline the connection and potential benefits from their integration, and conclude that *their synergy spans through the entire project life cycle* (Dave et al., 2013).

Dave et al. outline that *clash detection as one of the mechanisms of interaction of BIM and Lean goals*. Since this activity is executed virtually it *fosters a better control* and helps to avoid real construction mistakes, therefore it helps as well to avoid waste of materials and efforts, time, and costs. The *clash detection* is closely related to the interactions of *visualization and automated control* (Dave et al., 2013). The guide suggests as well that an early implementation of the co-developed models is useful as a support for communication with clients and users during early conceptual design stage. Since it fosters better understanding of their requirements (Dave et al., 2013). Such suggestions are consistent with integrated delivery methods and BIM approach enhancing collaboration at early project stages.

Furthermore, while structuring the knowledge, Dave et al. propose a *BIM maturity level model* to assist with identification of the particular journey, and suggest evaluating the BIM capability of every project stakeholder, where an integrated Lean and BIM maturity model, aiming to assist with strategy development and progress identification, it cites the following key criteria:

- *Transparent sharing of information,*

- *Synchronized visualization of models,*
- *Co-location of teams,*
- *Life cycle approach to modeling,*
- *Early involvement of stakeholders,*
- *Relational contracting,*
- *Target value design,*
- *Using BIM for production management,*
- *Virtual first run studies/optimising construction process using BIM,*
- *Delivering accurate as-built models,*
- *integrated BIM and FM (Dave et al., 2013).*

Such listing proposes the instruments for BIM and Lean efficient implementation. It emphasizes the importance of access to digital project information, use of BIM models and simulations, and their synchronized visualization. Which puts BIM in the core of the project development process and requires for relevant and easy interactions with it.

Moreover, following the research efforts on integration of BIM and Lean construction, Mollasalehi et al., also suggest that it would be beneficial for *more efficient identification and reduction of waste,* and *it would foster collaboration in integrated teams.* Thus, Mollasalehi et al. propose a “*Practical Waste Framework*” for waste control using BIM and Lean integration at the design phase, and validate it with AEC professionals through the surveys (Mollasalehi et al., 2016). First, they identified BIM and Lean construction features with most positive interactions relevant to the waste reduction approach, such as:

- *visualization,*
- *clash detection,*
- *4D scheduling,*
- *construction sequence planning,*
- *collaboration and communication (Mollasalehi et al., 2016).*

These conclusions are consistent with the previous studies, their particular focus is on waste reduction, however, they as well outline the usefulness of 4D BIM and importance of collaboration.

Naturally, an adoption of any innovation requires patience and presents challenges for every industry, company and individual professional. Sacks, Korb, et al., present observations and findings from the experience of BIM and Lean joint adoption and implementation with a scope on a journey of a development and construction company and through exchange of experience with other companies. They conclude that *BIM and Lean construction joint implementation is possible,* and even more is recommended since both approaches are beneficial in bringing an *increase of efficiency, productivity, competitiveness,* and complete each other (Sacks, Korb, et al., 2017).

In summary, BIM and Lean construction influences, interactions and uses were investigated by various studies, which emphasize that:

- *both paradigms empower and complete each other, and are capable to do so through all project cycle (Khanzode et al., 2005), (Sacks, Koskela, et al., 2010), (Dave et al., 2013), (Andújar-Montoya et al., 2019),*
- *both paradigms increase of efficiency, productivity, competitiveness (Sacks, Korb, et al., 2017),*
- *both paradigms foster collaboration and communication in integrated teams (Mollasalehi et al., 2016),*
- *an early implementation of the co-developed models is useful as a support for communication with clients and users during early conceptual design stage (Dave et al., 2013),*

- *Lean facilitates the use of BIM establishing a framework of distinct roles, responsibilities, organization (Dave et al., 2013, Andújar-Montoya et al., 2019, Michalski et al., 2022),*
- *BIM establishes an IT platform which enables project information flow (Sacks, Koskela, et al., 2010, Michalski et al., 2022),*
- *BIM becomes an enabler for Lean transformations, BIM implementation contributes to Lean goals and fosters Lean processes (Dave et al., 2013, Sacks, Koskela, et al., 2010),*
- *BIM models and visual production boards enhance the change of organization and culture (Sacks, Korb, et al., 2017),*
- *BIM contributes to more efficient identification, reduction and control of waste in design and decision-making (Dave et al., 2013, Mollasalehi et al., 2016, Andújar-Montoya et al., 2019, Li et al., 2019),*

The listed summary of selected interactions outlines the benefits of the joint implementation and confirms the ideas about BIM representing the technological core of the collaboration on a project, support for digital continuity, quality visualization and assistance to collaborative decision-making.

In addition, regarding in particular the 4D references in the studies of BIM and Lean principles interactions, the findings emphasize that:

- *4D BIM clash detection is one of the mechanisms of interaction of BIM and Lean goals (Dave et al., 2013, Mollasalehi et al., 2016),*
- *4D scheduling, construction sequence planning contribute to efficiency and lean goals (Mollasalehi et al., 2016).*

1.3.1.2 BIM, VDC and integrated approaches

VDC and Lean approaches

Virtual Design and Construction represents one of the early efforts on integration of digital models and simulations into collaboration and decision-making. VDC seeks to foster the use of digital tools, enhance collaboration and to eliminate various sources of inefficiency and errors. In VDC ***“BIM is the repository for all information – consistent, classified and coherent.”*** (Eynon, 2016), and since VDC aims to eliminate risks and potential issues using digital models, it aligns with Lean objectives of “waste” elimination as well.

As one of the initial studies, Khanzode et al. report about various significant benefits of an implementation of Lean Project Delivery System (LPDS), and of 3D and 4D use as a part of VDC during a design phase of a large scale project. They also emphasize some guidelines for using virtual building tools in a lean project, where they highlight the importance of establishment of collaboration and decision-making protocols, as well as of the clear outline of roles and responsibilities. In addition, regarding 3D and scheduling, they suggest to:

- *Pull design in small batches relevant to the construction schedule,*
- *Adjust the batches size coordination to use in the pull scheduling,*
- *Use 4D models for interactive construction sequencing and scheduling (Khanzode et al., 2005).*

Further, they investigate ***VDC application with Lean project delivery***, and propose guidelines, examples of tools and methods, as well as a conceptual framework for efficient joint implementation of VDC and LPDS (Figure 16) (Khanzode et al., 2006). More in detail, they illustrate the use of Product-Organization-Process model in alliance with the state of the Form, Function and Behavior of a project

to manage the project. Therefore, their approach, much like described earlier BIM collaboration research seeks to illustrate the synergy of technology, people, and processes.

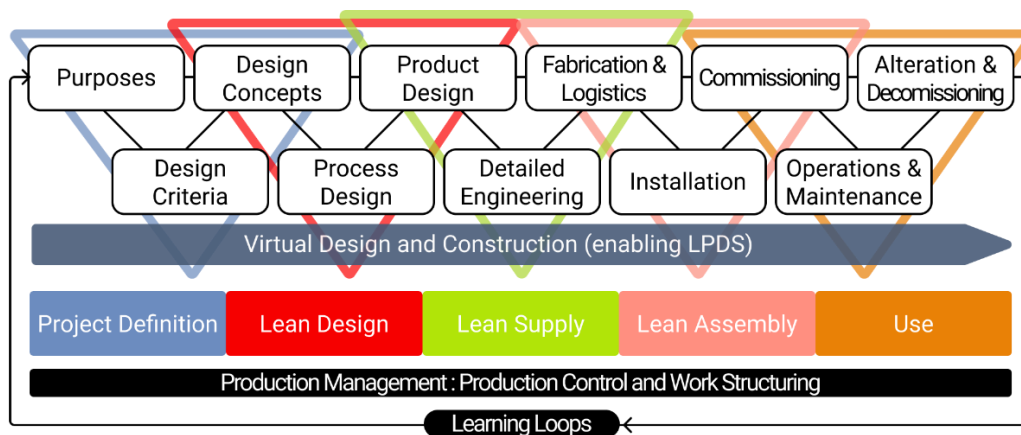


Figure 16 VDC enabling LPDS adapted from (Khanzode et al., 2006).

In addition, the researchers describe *4D models use for lean project delivery*. In the same line of research Khanzode et al. report on an implementation of VDC for coordination and illustrate that Lean improves VDC efficiency and flow, if it is used at the right stage and supports the Big room experience (Khanzode et al., 2008). They suggest to implement various tools, for example the *4D modeling as a tool supporting not only the design (product), but also enhancing the construction (process)* of Lean project delivery (Khanzode et al., 2008). The other tools are a part of VDC framework:

- *project 3D modeling, visualization, and coordination tools,*
- *project and process 4D modeling and visualization tools,*
- *organizational and process modeling tools,*
- *co-located or distant collaboration tools,*
- *effectiveness analysis and control techniques.*

Further studies continue to analyze VDC implementation from a Lean perspective, and report that various studies illustrated synergies between VDC and Lean since: *“Philosophy and culture have high synergies between Lean and VDC, management principles and the big ideas in general are common: collaboration in design and construction, optimization of the whole system and participation and involvement of the end users area all facilitated by VDC in lean implementation.”* (Alarcón et al., 2013). The analysis also *outlined the gap in implementation guidelines*, thus they present a summary of selected 20 interactions between VDC and Lean, which complete the BIM and Lean principles interactions matrix to assist with more efficient implementation (Alarcón et al., 2013).

From more related to the construction processes perspective, Sacks, Koskela, et al. state that IPD and Virtual Design and Construction (VDC) foster *“... BIM to provide an integrated project management and collaboration platform”* (Sacks, Koskela, et al., 2010), since they *create a legal frame and technological basis for collaboration*. They also investigate interaction of Lean and BIM, which could be *“... enabler or catalyst for lean transformation”* (Sacks, Koskela, et al., 2010). As outline Sacks, Korb, et al. *BIM enables the VDC* since it provides the project team with tools to bring the design information into a single source to be used for intensive and extensive collaboration and decision-making. Also, *VDC adds value to the project and assists with the Lean waste control*, since it relies on planning, simulations, studies and prototyping (Sacks, Korb, et al., 2017). Therefore, the use of 4D for these purposes is part of the workflow.

Sacks, Korb, et al. present feedback from VDC and BIM use for multidisciplinary and collaborative decision-making on a project’s MEP by “Tidhar” construction and development company. In the project, even though subcontractors were not directly producing the BIM information, they participated fully in design and construction *collaboration based on BIM model use as a virtual prototype and as a support for interactions, inquiries and problem-solving*. Therefore, the various aspects of the project were prepared in detail and various problems avoided or anticipated, which proved to be efficient (Sacks, Korb, et al., 2017). In addition, such approach places the continuous *improvement in a core of collaboration*. Thus, in this way not only technology in the heart, but also the scope on input from all experiences and skills, common knowledge, and expertise

Furthermore, Sacks, Korb, et al. also emphasize “Lease Crutcher Lewis” company’s experience with VDC standardization on a company level, with cloud BIM implementation and with methodical Lean practice. The feedback from the company members recognizes the benefits *of efficient coordination on weekly project review meetings with use of 4D clash detection and of a location-based schedule*. The implemented workflow requires from subcontractors to check the project BIM models and to prepare the future work packages to be used directly by construction teams onsite with the help of various *digital tools like personal touch-tablets or preinstalled digital workstations “BIM boxes”* (Sacks, Korb, et al., 2017). This workflow allows to the BIM packages to generate the construction tasks in a semi-automated way, and to the digital tools to support communication between the BIM and processes, it therefore assists with reduction of variability and batch sizes.

Fosse et al. study BIM and Lean construction in a context of “Skanska Norway” contractor and report on two use-case projects from a perspective of VDC uniting technologies and lean collaboration. The study outlines that *BIM supports the reliability of information and Lean the reliability of processes* (Fosse et al., 2017). The study reports on perceived benefits from the joint use of technologies and collaboration, with benefits such as:

- a gain of time during design phase,
- a perceived effectiveness of ICE meetings by their participants,
- a pull planning improving the quality of commitments,
- a better understanding of project and of the workload (Fosse et al., 2017).

The study reports that the *BIM model is an established core source of information in pull planning*, yet the study did not report on use of digital tools uniting BIM and LPS in one system, but on *separate use of 3D/4D BIM visualization tools and analogue or digital post-its*. They measured Integrated Concurrent Engineering (ICE) performance, LPS Percentage Plan Complete and BIM clashes. A summary of VDC overview model is presented in the Figure 16.

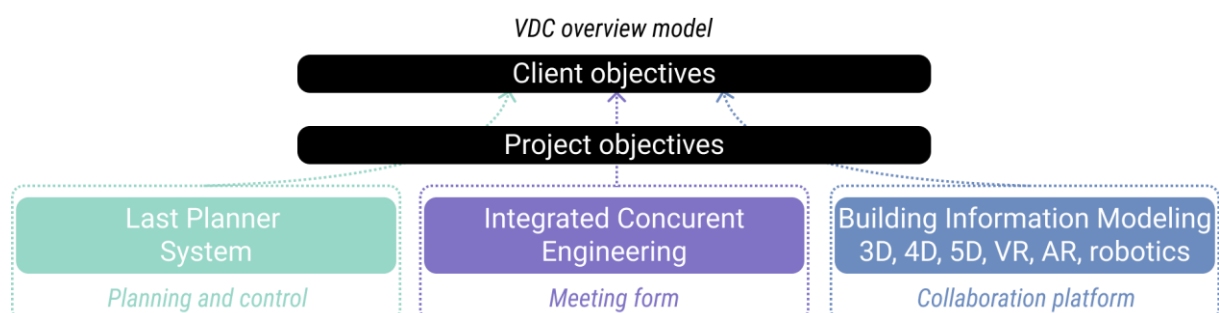


Figure 17 VDC overview model from Skanska Norway, adapted from (Fosse et al., 2017).

IPD and BIM integration

During the past decade various academics debated upon the potential benefits from a joint implementation of BIM, Lean construction, and Integrated project delivery. Liu et al. investigate the impact of BIM implementation on design and collaboration, and observe *that IPD and BIM adoption were occurring in parallel at the same time period*, emerging as a project delivery method IPD developed to be well adapted for BIM design and construction projects (Liu et al., 2017).

For example, BIM implementation allows *to manage complex projects in an integrated way* (Penttilä, 2006), and from the technological perspective a successful implementation of IPD relies on a choice of *an appropriate technology*, which will enable open and interoperable data exchanges within a transparent data structure (AIA, 2007). Therefore, project management and digital information jointly become more integrated. According to AIA guide, the *potential benefits of use of IPD regulating process and BIM regulating tools* on a project may be achieved *only when they are used together* (AIA, 2007). Since *BIM facilitates the integrated design* and construction, together they assist with better project quality delivery, as well as with improved management of construction costs and duration (Eastman et al., 2011). While from a functional point of view BIM “... allows the team to rapidly and consistently explore many design options rapidly and consistently, discuss how different designs will add value (or not), and how they will affect performance targets.” (Fischer et al., 2017; Ch.3), but from the organizational point of view it creates “the neural system” for IPD (Fischer et al., 2017; Ch.10). Which illustrates that the joint implementation approach *seeks to install a holistic system*, to foster integrated organization and collaboration, and placing the digital tools in the core.

BIM implementation and management of the exchanges would reinforce the IPD, and together they may establish *a firm basis for digital continuity of data, processes and practices*. (Eastman et al., 2011). However, within the IPD framework, the *integrated information* is in the core, much alike BIM is in the core of a socio-technical system. Kahvandi et al. review IPD research trends, and outline that IPD and BIM joint implementation is one of the major topics in research literature, together with main principles and challenges of IPD, and consider that: *“BIM is a tool for better and more systematic implementation of IPD principles along the project life cycle.”* (Kahvandi et al., 2017).

Furthermore, as identified in research by Jin et al. BIM as the digital platform for more efficient design and delivery *“... does not only ask technical advancement (e.g. enhanced interoperability between different software platforms), but also the IPD approach.”* (Jin et al., 2019). Erazo et al. provide a feedback from use of BIM and IPD tools to *facilitate access to the information* for all stakeholders and reports a *reduced responses time* for requests of information or decisions inside the team. Also, it reports that the effort to enhance collaboration from the initial stage reduced requests for information during the construction (Erazo et al., 2020).

The use of IPD and BIM together is beneficial for the project team collaboration and decision-making. *Regarding information organization, Ashcraft suggests organizing an IPD system in a way that should create a framework for information as common basis of understanding and of project context*. On the top of such common basis develops *an environment for team collaboration and interactions, which provides an access to the information* to all project team members (Ashcraft, 2012). *Since BIM creates a common basis and language among project parties, thus it can assist with an integrated team cohesion* (Rokoei, 2015). *In addition*, a previous positive experience with BIM adoption, establishes a basis and fosters trust and communication improvement in an integrated project (Liu et al., 2017).

BIM and IPD bring the “construction knowledge” to the design team through the *early involvement of the contractors* (Eastman et al., 2011). Furthermore, as Talebi outlines in the research studying BIM

and IPD, BIM already brings many changes to the traditional design process. It accentuates the design adjustments during the early design phase, where the cost is lower, thus it does not follow a waterfall model, but *more integrated project design*. In addition, the integrated and collaborative project delivery methods would be beneficial for a BIM-based project, since BIM implementation *requires from the project team to collaborate closely* (Talebi, 2014). Fakhimi et al. take a perspective on definition of collaboration from IPD and Lean point of view and state “*Collaboration is a data-centric activity while integration is a knowledge-centric activity*”, where collaboration is the first step to integration (Fakhimi et al., 2016).

Moreover, a study of the joint implementation suggests that a project team should use the models augmented with schedule and cost information for efficient co-located collaboration to avoid misunderstandings, and reports from a use-case that project meetings with such models use were more efficient to resolve project issues than the meetings without the models. (Fischer et al., 2017; Ch.14). Therefore, the implementation of nD models as supports for collective decision-making has already demonstrated beneficial impact on a project.

The abovementioned studies outline benefits and synergy of the use of BIM for integrated information use while the work processes and organization are structured and guided by IPD, Table 4 proposes a summary of several joint implementation effects of BIM and IPD.

Table 4 Summary of effects of joint implementation of BIM and IPD

| Joint implementation effect | Studies |
|---|--|
| IPD and BIM empower each other, and their joint implementation is required to achieve efficiency and ensure benefits for the project and for collaboration | AIA, 2007, Eastman et al., 2011, Talebi, 2014, Kahvandi et al., 2017, Fischer et al., 2017, Erazo et al., 2020 |
| BIM becomes an enabler and establishes a basis for integrated information and for fluent data exchanges, becomes a technological core of IPD | AIA, 2007, Eastman et al., 2011, Rokooei, 2015, Fakhimi et al., 2016, Fischer et al., 2017, Jin et al., 2019 |
| The joint use of IPD and BIM requires closer collaboration and fosters transparency of the process | AIA, 2007, Talebi, 2014, Rokooei, 2015, Fakhimi et al., 2016, Fischer et al., 2017, Erazo et al., 2020 |
| For an IPD integrated team, BIM creates a common and accessible, more interactive and collaborative digital environment, which fosters the use of visualization and simulations by all team members | Ashcraft, 2012, Fischer et al., 2017, Erazo et al., 2020 |
| An integrated design is enabled by BIM implementation | Eastman et al., 2011, Talebi, 2014 |
| An integrated management of complex projects is enabled by BIM implementation | Penttilä, 2006, Jin et al., 2019 |

Key points of 1.3.1

BIM implementation with Lean construction, and with Integrated approaches

- Joint implementation of BIM and Lean construction improves efficiency and productivity. Despite identification of their interactions for design evaluation and multidisciplinary design collaboration, as well as for 4D schedule management, the implementation reports are not numerous, and often focus on visualization quality improvements. However, there is a lack of tools and methods encompassing both approaches into a holistic system. Moreover, Lean principles foster closer collaboration of construction and design teams, therefore such system must facilitate collaboration as well.
- Collaboration is the first step for integration, and BIM is the basis, enabling data integration and establishing support for project team members interactions, which creates a common and accessible, more interactive, and collaborative digital environment. In addition, co-located collaboration represents one of the key elements to an integrated approach.

1.3.2 IPD, Lean construction and BIM/4D

Each of the approaches fostered shifts in AEC and brought many benefits and challenges. Their joint implementation requires for different adjustments, for an installation of a holistic and complex system. IPD and Lean construction have their own interactions with BIM, and influence collaboration in their own way, as it was outlined in previous sections. The following subsection aims to outline the existing research on BIM, Lean construction and IPD synergy, highlight benefits and challenges (1.3.2), and to outline in particular the place of collaboration and 4D use in a context of their synergy (1.3.2).

1.3.2.1 Synergy of IPD, Lean construction and BIM

Uniting concepts and approaches

Any innovation follows a cycle from awareness to full implementation. As suggested by Eastman et al. *IPD implemented with BIM support digitally driven project design and delivery, and with lean construction techniques assure benefits to project management* (Eastman et al., 2011). Therefore, the path toward synergy of these approaches has already been in motion.

Miettinen and Paavola outline that from techno-economic perspective an economic cycle of development requires invention and adoption of a new technology, and its full implementation requires development of new methods of organization. Such outline shares similarities with socio-technical perspective since it encompasses technology and the need for new methods. However, the techno-economic perspective *emphasizes that a cycle of several decades is required, which includes the shifts on various levels*. Thus, currently AEC faces the challenge “... to reform the organizational, institutional, and contractual practices that allow the full deployment of BIM.” (Miettinen and Paavola, 2014). Such requirements for changes in different aspects foster a development of various studies and pilot projects.

In addition, Fakhimi et al. outline that due to complexity of construction industry there *is a need for new theories and perspectives on performance improvements* including technologies, organization and management (Fakhimi et al., 2016). Likewise, since the shift to Lean thinking embodies a paradigm change, Sacks, Korb, et al. outline *the need to understand not only the innovative tools and methods but also the philosophy*, as well as to *implement training and gathering of experience* within every company. Lean also puts the *ability to improve in the core* of all the processes and relies on conditions and efforts to implement the improvements (Sacks, Korb, et al., 2017). From a socio-technical perspective, Lean construction, despite direct influence on processes, may be also seen as a social system since it creates the environment and provides tools for collaboration of different stakeholders (Al Balkhy et al., 2021).

An analysis of ten projects across the USA implementing IPD and Lean construction concludes that their implementation proved to be complementary and beneficial. Since, they foster collaboration and improve efficiency, with *IPD providing framework for collaboration*, and *LC providing collaborating teams the tools* for efficiency improvement (Cheng et al., 2016). Digital age transformed the usual AEC cooperation into a real-time, more close and creative collaboration, with shifting the decision-making responsibilities from architects to *more collective decision-making* (Fischer et al., 2017; Ch.7). In addition, Sacks, Korb, et al. outline that not only BIM and Lean present positive effects on report increase of efficiency and productivity, but also highlight the potential of an integrated approach, where: *“Integration of the entire value system from conception to project completion is a key ingredient for exploiting the benefits of lean and BIM.”* (Sacks, Korb, et al., 2017). With Lean diffusion to various industries, Tezel et al. evaluate Lean thinking in highways construction in UK, and report strong

motivation. However, there are still limited adoptions of the Lean construction techniques like the Last Planner System and Visual Management, and efforts towards integration with BIM (Tezel et al., 2018).

Fischer et al. emphasize that with BIM “... *and new management approaches—Lean, Agile and Integrated Project Delivery (IPD)—we are realizing the opportunity and the need to expand input and use data and information to make the best possible decisions.*” (Fischer et al., 2017; Ch.7), and propose a concept of evidence-based design (EBD) which benefits from the synergy of the approaches and fosters collaborative decision-making. However, such an approach is still in development.

As observed by Mechado et al. from the literature and case-studies review, even though the adoption of IPD, Lean construction and BIM fosters various benefits to construction and project performance, as well as it fosters stakeholder’s implication, these methodologies *have not been widely used together*. However, their joint use improves effectiveness of each methodology, and “... *synergy improves mostly the communication level and team collaboration during the whole construction process.*” (Machado et al., 2020), which leads to increase of design and construction efficiency, decrease of number of conflicts, construction time and costs.

Research approaches to IPD, Lean construction and BIM synergy

For the last decade various authors investigated synergetic implementation of BIM, Lean construction and IPD, with studies focusing on bilateral, or trilateral implementation, on framework design or on feedback from use-cases. Most of the studies take a perspective where BIM covers technology-related aspects of project development, while Lean construction and IPD focus on social aspects, organization, processes, and teams.

A study of BIM and Lean construction implementation by Dave et al. outlines the importance of using *collaborative planning which would be fostering integration during design and improving accuracy during constructing phases* (Dave et al., 2013). Their study also seeks a way to balance people, process, and technology issues, where *Lean construction is people and process oriented, and BIM represents a technological platform*. Thus, they highlight from previous experiences that for a technology adoption the balance of organizational pillars would be close to 40% process – 40% people - 20% technology. This approach proposes a holistic view on interactions of BIM, Lean construction and foresees need for integrated delivery. Though, it perceives BIM as a technology, which facilitates the discussion, but does not fully include the managerial aspects of Building Information Management, to encompass not only the model, but also the collaboration protocols and processes which are crucial to successful BIM implementation. Additionally, Dave et al. propose guidance for Lean construction and BIM implementation, and suggests various actions to overcome:

- *Process issues – strategical approach to changing the business model and flows,*
- *People issues – establish collaboration with the entire supply chain,*
- *Technology issues – foster implementation process customized for a company (Dave et al., 2013).*

These actions would not only be applied to a pilot project but foster change in a company’s culture. Much like with BIM manager, a BIM-Lean champion may become a guide for such changes. In order to start the integration, a BIM company may begin Lean adoption with collaborative planning, Lean work structuring or visual management, with the main goal of uniting all the people (AEC professionals of the company) with the same goals and Lean approach. This guidance highlights that the *4D use for collaborative planning not only enhances BIM benefits, but also becomes a support for the integrated implementation* of BIM and Lean construction.

Further, Fakhimi et al. review IPD, Lean construction and BIM bilateral collaborations and suggest a need for their trilateral collaboration, where the approaches “... greatly aiding to improve productivity and efficiency via enhanced collaboration and integration.” (Fakhimi et al., 2016). The researchers review the literature on awareness of the topics, and they analyze it through a prism of process, people, and tools, present a summary of main reported bilateral collaboration barriers and benefits. They state that “... IPD structures people's interactions and incentives, LC increases value and efficiency and BIM provides transparency and a single source of truth.” (Fakhimi et al., 2016).

The analysis identified a gap presenting *lack in trilateral collaboration*, where IPD establishes legal framework for lean project delivery with an aid of BIM. Therefore, they propose a scheme for a synergy of the approaches Figure 18, which “...enables a level of collaboration that not only improves efficiency and reduces errors but also enables exploration of alternative approaches and expansions of market opportunities.” (Fakhimi et al., 2016).

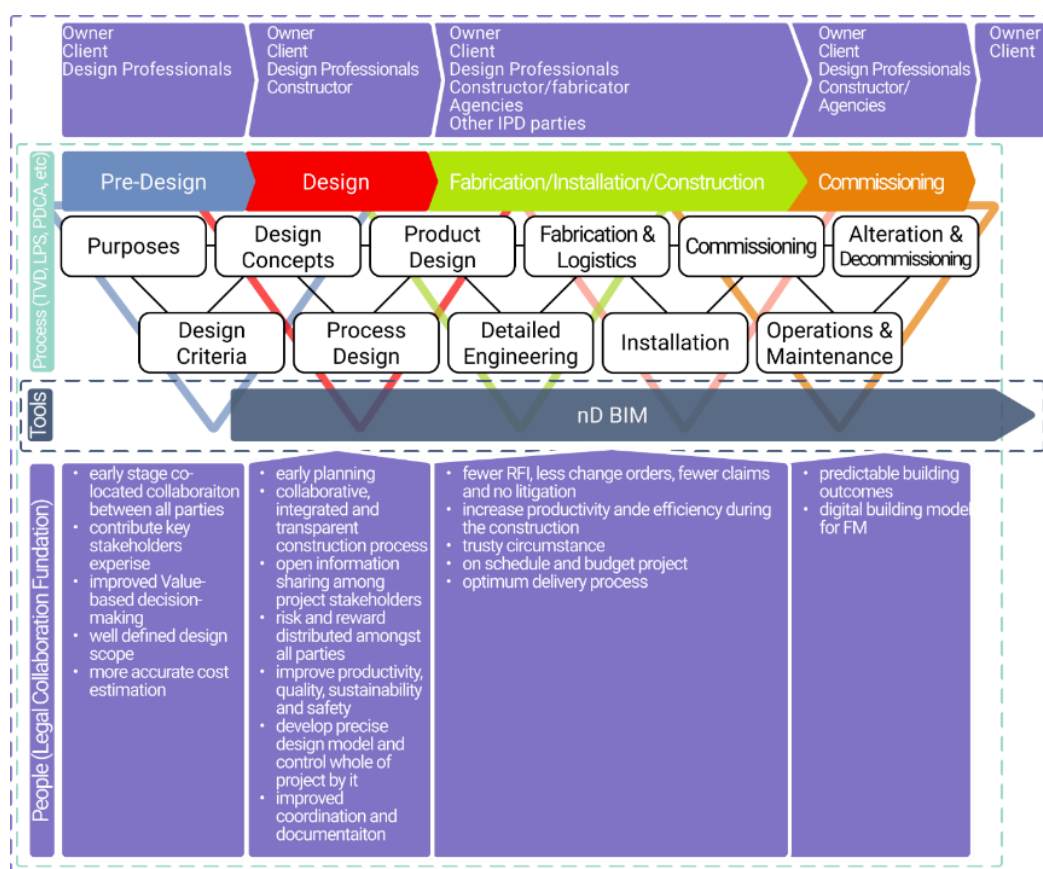


Figure 18 IPD, Lean construction and BIM trilateral collaboration scheme from the perspective of People, Process and Tools, adapted from Fakhimi, et al. 2016

The proposed scheme by Fakhimi et al. was not described in detail, yet according to the illustration it seeks to implement Lean Project Delivery System (LPDS) main stages as elements managing project processes, nD BIM as managing tools, and provides a description of collaboration and project progress steps by the phases. The researchers also state that IPD and LC focus on process and people implementing techniques, yet they do not use specific tools, however IPD is strongly dependent on BIM tools implementation, and LC has a variety of lean specific tools as well. In addition, in this approach BIM is perceived only as a technology, however it does not introduce framework for cooperation, which

would ignore its influence on collaboration structure and collaborative design (Fakhimi et al., 2016). Despite the complexity of the proposed schema, a more detailed description and feedback from a use-case or a scenario would be useful to reinforce the proposed ideas.

Another research by Machado et al. outlines that implementation of IPD, Lean construction and BIM improves *construction performance and project stakeholder collaboration*. However, a framework of their joint implementation *has not been widely exploited*. Machado et al. suggest that the joint use of IPD, Lean construction and BIM would be more effective, since their synergy improves communication and collaboration, creates a *collaborative environment allowing to “... decrease the number of conflicts, enhance the design and construction process efficiency, and the time and cost spent on the construction phase are also lower than initially planned”* (Machado et al., 2020). The synergy of the approaches and the abovementioned benefits, as well as the role of collaboration and 4D use in successful implementation contribute to our research subject and provide basis for a hypothesis.

Further investigating the subject, Nguyen and Akhavian analyzed 72 real projects to study IPD, Lean principles and BIM (ILB) synergetic implementation in various combinations using project performance, cost and schedule criteria (Nguyen and Akhavian, 2019). Their analysis reports the significant improvements in terms of schedule performance with ILB compared to using only BIM yet does not observe significant improvements of cost performance as a single metric. The analysis also illustrates improvements on joint cost and schedule performance with full ILB implementation.

Also, using grounded theory, Nguyen and Akhavian identified influential categories of a successful project and associated them with ILB synergizing concepts from case studies as summarized in Figure 19 (Nguyen and Akhavian, 2019).

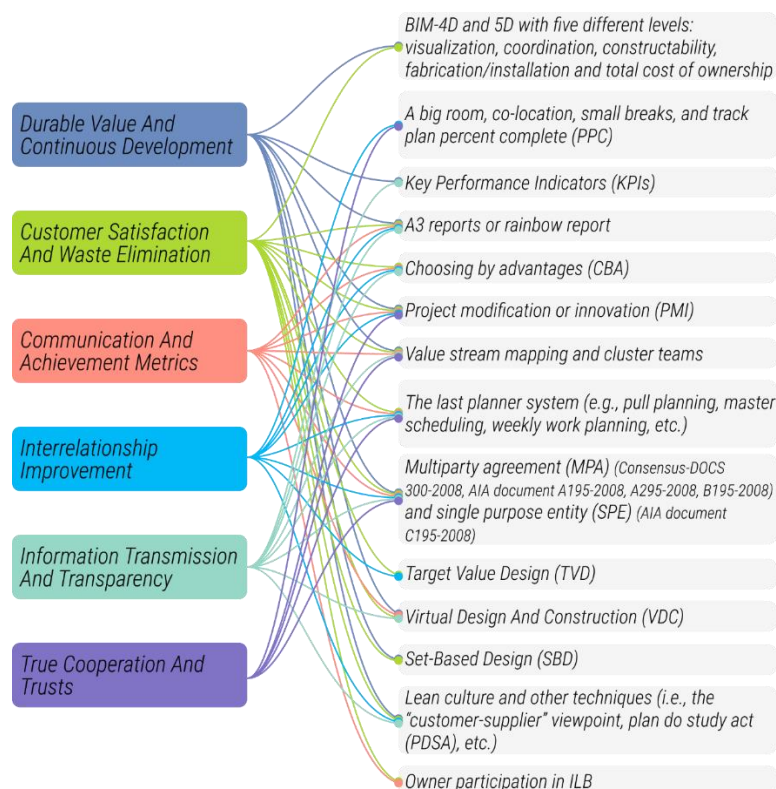


Figure 19 Project success categories and ILB concepts synergy according to (Nguyen and Akhavian, 2019)

Thus, Nguyen and Akhavian outline that 4D BIM use for visualization, coordination, constructability, fabrication/installation is beneficial for the category of durable value and continuous development, and together with LPS implementation 4D BIM use is beneficial for customer satisfaction and waste elimination. In addition, they identify the collaborative and co-located design and decision-making together with LPS and other concepts contribute to the Interrelationship Improvement and to the true cooperation and trust categories (Nguyen and Akhavian, 2019). The proposed categories and concepts present a clear and detailed basis for synergy description, yet do not emphasize in particular a category which would imply elements of all the three approaches. Thus, it illustrates that despite the clear beneficial influences of bilateral implementation, an outline of trilateral influence is less distinct.

1.3.2.2 4D BIM and collaboration in an integrated context

The observations presented by Sacks, Korb, et al. from the experience of BIM and Lean joint adoption and implementation by a construction company emphasize that not all of the aspects of each approach sustained the implementation to become a part of future standard practices (Sacks, Korb, et al., 2017). Among other elements of the experience feedback, they outline certain practices that became a part of company culture:

- *use of BIM and 4D simulations for a detailed production planning and monitoring,*
- *use of weekly work planning as a part of the LPS,*
- *early involvement of construction at decision-making for design development to enable changes and efficiency of design,*
- *use of BIM in the Big room^{vi} for design and coordination for all projects.*

The abovementioned practices represent the selection relevant to our study subject. They also emphasize the categories of 4D use for collaboration in a context of BIM, Lean construction, and Integrated Project Delivery.

Visualization and collaborative planning

Quality of visualization and possibilities of deeper, clearer understanding of construction processes represent the tangible benefits from 4D use. Sacks, Koskela, et al. highlight that BIM provides a useful and efficient environment for project visualization and for simulations, where **4D tools** visualize time and space conflicts, thus *“This enables process optimization improving efficiency and safety and can help identify bottlenecks and improve flow”* (Sacks, Koskela, et al., 2010). Furthermore, another study observes an expansion of 4D use by contractors in UK, and it outlines **4D planning** as another interaction of BIM and Lean construction, where collaborative planning represents one of the Lean tools and fosters collaboration, where the 4D fosters clear visualization for all project participants, assisting to *“... gain a deeper understanding of the planned activities in advance”* (Dave et al., 2013), and 4D proves to be more efficient in comparison to the use of 2D drawings during planning meetings.

Lean construction is about building **reliability**, and is different from production in various ways, for example the work is released through planning, thus *“... measuring and improving planning system performance is the key to improving work flow reliability.”* (Howell, 1999). In addition, collaborative planning *“ ... maximizes positive iterations and reduces negative iterations”* (Lichtig, 2010). Therefore, lean planning is one of the key activities for a project’s success and a task for a project team. In IPD, the **Intensified planning and 4D** represent some of the main principles, since they foster efficiency increase

^{vi} Co-located collaboration physical environment enhanced by digital tools fostering collective design and decision-making

and result in savings during construction (AIA, 2007). An overview of *4D BIM use with IPD* perceives a *potential in an early detection of problems and a possibility to reinforce the collaboration* for an integrated team (Aminu Umar et al., 2015). Thus, these perceptions of 4D BIM represent a common ground for the approach's synergy.

A report on a use-case of joint implementation of BIM and Lean construction practices for a project of Sutter Health Eden Medical Center Hospital, describes the use of value-stream mapping and pull planning sessions. At the sessions, the project team collectively contributed to planning and handoffs for BIM design using a value-stream map and sticky notes as a support for decision-making which was displayed in a shared collaboration environment of a Big Room, and the BIM execution plan was consequently based on the map. Such approach proved to be efficient, and the map was eventually transformed into a push and pull planning (Fischer et al., 2017; Ch.8). On another use-case Lean construction approach allowed to *reduce construction time* by two months due to thorough attention to planning and to *"... the shorter time spent in the implementation of various activities."* (Machado et al., 2020).

LPS as a tool for planning and management

Furthermore presenting in detail the use of Lean construction planning tools implementation, William Lichtig emphasizes that LPS® *"... incorporated the idea of automation by distributing responsibility for developing and maintaining the planning model to the Last Planners"* (Lichtig, 2010), thus they would collaborate, create the work plan and therefore improve reliability.

Sacks et al. present feedback from the *joint use of BIM and Lean lookahead schedule, pull planning and Last Planner® System* provided by *KanBIM tool* (2.2.1, Figure 59), which improved *visualization quality and reduced wastes* (Sacks et al., 2011). Which illustrates the importance of relevant information visualization and of the relevant approach to the construction planning and management. In a similar way, a report from a use-case presents that IPD *"... provided an environment where a realistic and information-rich schedule could be produced"* (Fischer et al., 2017; Ch.13), where the researches distinguish a "macro" level of 4D which simulates the flow of the whole construction site, and a "micro" level 4D that illustrates the work sequence of a lookahead schedule. The levels followed again the idea of relevant information visualization and use for decision-making.

Toledo et al. present the use-cases of BIM and LPS® joint implementation which *enhanced communication of project stakeholders at planning meetings*, however BIM and LPS® did not occur at Lookahead level, but on weekly planning level. They report *a reduced project variability* from the joint use, as well as that more project roles were participating at the meetings, which became shorter but maintained an efficient project understanding (Toledo et al., 2016). Among several observations and findings, they summarize several *requirements for efficient integrated implementation of BIM and LPS®*, and for collaborative planning and decision-making. In detail, concerning 4D and decision-making they outline that:

- *project Master plan should be joined with a 4D model and used by all project team members,*
- *display of project boards and their regular updates are crucial for efficient construction,*
- *project team members must have access to the Lookahead planning and possibility to consult it before project meetings,*
- *RFI support is necessary for collaborative lookahead planning,*
- *decision updates concerning design and construction constraints should be available to last planners (Toledo et al., 2016).*

These requirements assist with protocols and tools design, and guide the potential actions to take to facilitate the implementation.

From a description of an experience of Lean Construction and BIM implementation at Skanska construction company in Finland, another study outlines a use of **BIM 4D clash detection and simulation** with different schedule scenarios for planning optimization and for risk evaluation. Such use of BIM tools was also a part of make-ready LPS® implementation, and enhanced access to project information, as well as **improved communication and collaboration** (Sacks, Korb, et al., 2017). The researchers emphasize that BIM not only assists with decision-making, but also with a rapid and efficient communication between general contractor and construction teams on site. However, the authors still identified a **need to improve communication skills** and **a need to help employees to detect and manage problems** in their production systems, and a need to assure the relevant devices use to bring BIM and Lean on site. The highlighted needs may be considered by a more holistic and integrated approach to the workflow's organization and collaboration.

Fischer et al. present various use-cases of IPD, BIM and Lean joint implementation. A report on a use-case of implementation of detailed 4D simulation based on suggestions of trade supervisors and on Last Planner® System highlights the beneficial results of **reduced field issues**, with significantly low RFI related to on site conflicts, and improved construction **site safety**, and **work finished ahead of schedule** (Fischer et al., 2017; Ch.12-).

Another report on a use-case of collaboration with IPD, integrated Lean construction planning and scheduling practices presents the used methods, which included LPS® phase schedules and short interval work plans, together with pull scheduling and daily updates on commitments, and which consequently assured the cost-reduction goals (Fischer et al., 2017; Ch.8). This approach fostered the team to create conditions for decision-making at the lowest possible level, and therefore to avoid time-consuming approvals from various levels. In summary, the design team achieved cost reduction goals, and submitted on schedule fully coordinated design packages and met almost all of set performance targets.

For another use-case the project managers strategy focused on “... **need the right people planning in the right level of detail at the right time.**” (Fischer et al., 2017; Ch.10). The usability of a required by legislation detailed CPM schedule for production planning and supporting the right works executed at the right time at production planning was not optimal, since it may not provide the right detail at the right time. Also, the project team set a goal on maximizing the construction efficiency. Initially, the team had some concerns that traditional construction scheduling and management would not support this goal. Therefore, they **combined CPM and LPS® and report a better control for management and early completion** of the project (Fischer et al., 2017; Ch.10). Despite the positive feedback, the whole project team had to learn to “think differently” to implement the new approaches, therefore the new collaboration methods, tools and skills had to be developed.

Early team integration and collaboration

To bring benefits, all three approaches must be accepted and used by all project disciplines, and not only for design but also to support construction. Legal, organizational and management structures must enforce the implementation. In addition, the use of 4D visualizations and simulations is not only beneficial for more efficient design but also becomes “**a platform to discuss and interpret the values of the owner and the end users**” (Fischer et al., 2017; Ch.3), therefore it creates more democratic environment for decision-making and collaboration.

William Lichtig emphasizes the feedback from implementation of Lean construction principles on Sutter Health project, and outlines that an Integrated Form of Agreement (IFOA) provides the structure for implementation of Lean and a legal structure for collaboration. The study highlights that the architect and the construction manager/general contractor take the role of a Core Group which supports IPD, and operates according to the Integrated Agreement which “... *calls for executive oversight for the Core Group to foster learning and a collaborative environment.*” (Lichtig, 2010). And to foster the optimal collaboration environment all the participants should view themselves as equal and stay focused on collaborative problem solving (Lichtig, 2010).

In addition, the *major stakeholders must be involved on initial project stages*, to contribute with experience and knowledge during design, and therefore improve decision-making. In particular, the authors outline that: “*Tasks such as scheduling, value engineering, construction budgeting, construction document co-ordination, record-keeping and consultations can be performed with the help of BIM used in the pre-construction phase.*”(Dave et al., 2013). Therefore, 4D use is a requirement and a first step for a collaborative and integrated project.

Though, to assist with BIM and Lean implementation there is a need for a *strong motivation* for change and a significant commitment to *invest resources* (Sacks, Korb, et al., 2017). IPD share similar barriers and challenges to BIM and Lean construction implementation of need for trustful collaboration, technology acceptance and implementation, legal structure to support work, as well as the innovation acceptance (Fakhimi et al., 2016). From a project management perspective IPD and 4D, 5D (3D+costs) BIM use *fosters more collective and efficient decision-making since it allows better control of construction activates, time, cost, and a capability to review alternative scenarios for construction* (Rokooei, 2015).

In addition, according to Fischer et al.: “*Planning is a group activity, with those responsible for executing work taking responsibility for coordination and scheduling. Everyone owns the constraint log.*” (Fischer et al., 2017; Ch.13). The scheduling and coordination are typically the tasks that would benefit from collective input, and “... *Regular pull scheduling is also a useful coordination exercise because it focuses on the decision interchanges between teams.*” (Fischer et al., 2017; Ch.9), the project team members request more information for pull scheduling, and therefore enhance their coordination and avoid issues, *mitigate negative impacts and risks* (Fischer et al., 2017; Ch.9).

Machado et al. also present feedback on two use-cases and report that project team members were closely collaborating not only during the construction, but also during the design phase. However, *the role of the leader was shifting from phase to phase, which is natural due to the fragmented nature of the AEC professionals’ competencies*. Also, IPD allowed to select relevant project participants during the pre-planning phase and establish decision-making flow. *The use of BIM for collaborative decision-making* fostered more clear vision of the project activities since “... *the accomplished simulations and details enabled the use of just-in-time delivery and prefabricated elements on the construction site.*” (Machado et al., 2020).

Management transformation

IPD suggests to organize team work to “connect people’s actions, information, and decisions.” (Fischer et al., 2017; Ch.8), in addition with implementation of BIM and Lean construction the project management, work organization and team interactions the usual practices would come through a variety of changes. An approach to a management of a project integrating BIM, Lean construction and IPD, or only one of them, would differ from the traditional approaches.

Also Fischer et al. present a feedback from a use-case implementing IPD and Lean where a team used: Conditions of Satisfaction (CoS), Waste, Pull planning, Last Planner System®, Plan-Do-Study-Act. (Fischer et al., 2017; Ch.15). This approach involved everyone responsible to the task achievement into the process of decision-making with pull planning, which relied on sticky-notes to support this activity. The approach assured the continuous improvement as a part of an iterative process with the Plan-Do-Study-Act method and outlined the importance of building trust between team members. Therefore, these aspects had to be considered by the project managers. In addition, the feedback describes a workflow of weekly co-located collaboration meetings for pull planning to integrate the new tasks into a lookahead planning, and cloud-based digital production planning. A particular tool for construction monitoring and management relied on the metrics evaluation, which were demonstrating the efficiency of the approach with Plan Percent Complete (PPC) = 85%, Tasks Anticipated (TA) = 50%, Tasks Made ready (TMR) = 45% ” (Fischer et al., 2017; Ch.15). These various elements of project management contributed to the successful implementation of IPD and Lean construction approaches, however, they fostered changes and need for adaptation of the usual practices. (Fischer et al., 2017; Ch.8). For an integrated project, a preliminary schedule accrues during conceptualization phase, which is different from “traditional” project delivery methods. The schedule becomes an important metric to measure success of the project and becomes linked to a virtual model during design development.

Saeed Rokooei argues that from a project management perspective the joint implementation of IPD and 4D, 5D BIM are ***beneficial for the project team activities since it facilitates project monitoring and control*** (Rokooei, 2015). Since the design and construction meet during 4D scheduling and construction sequence planning, Mollasalehi et al. in ***“Practical Waste Framework”*** for waste control using BIM and Lean integration outline that the ***4D model facilitates the reduction of such wastes as: waiting, unnecessary movement, defects, excess inventory.*** In addition, they identify the root causes of waste: ***change orders, decision-making, lack of information exchange, poor communication, lack of knowledge and the right mindset*** (Mollasalehi et al., 2016). They propose to survey the waste by enhancing identification of the root causes, planning and enhanced communication with the help of 4D visualization (Mollasalehi et al., 2016). Such a survey and waste management also foster changes in traditional project and construction management.

Interactivity and accessibility for collaboration

Among the number of requirements for successful implementation of each approach separately or together, the idea of enhanced collaboration is often supported by the tools enhancing interactivity and access to project information or to the delivery techniques. With various disciplines gathering for design and decision-making the need for a relevant collaboration environment is crucial for optimal results.

A study of a use-case on co-located collaborative scheduling in a “Big Room” within the IPD approach, reports that such settings allowed an early involvement of the construction team members and even the future users during ***design phase and enabling lean processes.*** The feedback also emphasizes the benefits for schedule and cost optimization from the ***construction team participation at the user group meetings*** with the design team, and the benefits to the users as well. They followed the budget status and schedule milestone goals, understood better the project, resulting in more effective decision-making (Fischer et al., 2017; Ch.14). One of the enablers of such productivity is the collaboration environment which fostered easier and more efficient interactions and more integrated workflows. The environment would first provide a physical space relevant to the meeting requirements, and second the digital tools and supporting protocols to enhance the collaboration, use of nD BIM and lean practices,

as well as the integration of tools, teams and approaches. The improved visualization, access and interactivity may be of service to the enhancements.

Further, another use-case of collaboration with IPD and Lean construction planning implementation for a hospital project also described the co-located collaboration meetings experience of a large multidisciplinary project team with the help of an “iRoom Lab” presenting the users with big touchscreen displays. Such a setting fostered not only better communication, but also improved the interactivity of project data. Fischer et al. report that few project team members had experience with integrated teams or VDC, however they have *quickly focused efforts on achieving elevated level of collaboration* for value engineering and design detailing. The project team states that the members became real collaborators due the experience of a Big room. Also, from the co-located design experience, they have noticed the positive impact from creation of an integrated team. The team resolved most of the design issues in 30 minutes, or the issues which were resolved in a day would have typically taken weeks to be solved (Fischer et al., 2017; Ch.8). Such feedback highlights the importance of interactivity quality and colocation influence on integration team collaboration.

In a project the *4D models can be developed by any project team member with access to BIM and to schedule*, yet they must be a result of a collective effort which incorporates experience and expertise (Fischer et al., 2017; Ch.12). Therefore, they require for more democratic interactions and for easy inputs into project’s digital information flow, and they should be a part of a continuous dataflow. Fischer et al. *foresee a development of new tools to support the joint harmonious implementation of IPD, Lean construction and BIM*, and to integrate emerging practices and reinforce the experiences (Fischer et al., 2017; Ch.8). Ighaish and Abrishami developed *a framework to implement 4D solution aligned with IPD* which focuses on 4D processes, and identified a *gap in existing solutions for integrated implementation* and argue about potential benefits from IPD analysis tools united in a single platform (Elghaish and Abrishami, 2020). Therefore, new more integrated and interactive tools, assuring data continuity and accessibility, adapted to the holistic approach and collaboration goals must become a part of the collaboration environment.

Summary of 1.3

Towards synergy of BIM/4D, Lean construction and IPD

- Several studies outline benefits from bilateral implementation of digital tools and construction or management approaches. The implementation is similar in a way that it puts technology in a core of a socio-technical system, and is encompassed by collaboration, decision-making, management, and culture shifts. However, due to the relevant novelty of adoption and implementation of the approaches, to complexity of design and construction projects, to the need for development of new frameworks, their synergy is still in development.
- 4D BIM and Lean tools are essential for efficient project delivery and for collaborative planning, control, and monitoring of an integrated project.
- The improved project understanding flows and reliability; therefore, a clear, reliable, and accessible visualization of project information is necessary for collaborative planning. Furthermore, the collaborative planning fosters waste control, optimization of project processes and sharing knowledge and experiences. However, it requires establishment of a collaborative environment comprising tools, processes and people organization and interactions. Interactivity and accessibility improve collaboration quality as well. Therefore, relevant tools and protocols are necessary to support such collaboration.

Summary of Chapter 1

BIM/4D, Lean construction and Integrated project delivery overview and use for collaboration

- Digitalization and Building Information Modeling and Management fostered various advancements and challenges in AEC. Moreover, construction scheduling and project management approaches are advancing with a focus on optimization, digitalization, collaboration, and integration. The emergence of new tools, as any innovation, aspires for novel uses providing solutions to the existing issues or offers the new functionalities. However, at the same time it outlines the requirements for further developments, novel uses, and challenges (B2). The innovative tools appear as solutions to existing problems or as opportunities for novel functionalities. Since they are to be continued with further development and other novel uses, the requirements for subsequent work emerge.
- BIM implementation places intelligent nD models in the technical core of the socio-technical system. The core is encompassed by social aspects including synchronous collaboration, coordinated practices and institutional culture. In addition to the various benefits for a project, efficient BIM implementation requires digital information continuity, interoperability to support collaborative design and avoid data losses, relevant workflows and protocols to organize the work and collaboration, development of new skills by AEC professionals (B1, B2).
- The advancements in construction planning and management alongside BIM advancements brought various innovations and benefits as well. Lean construction development and implementation brought a variety of benefits offering responses to the need for more efficient planning, for process location-based scheduling, and for waste control. In addition, it answered the need for more collaborative and integrated decision-making, and for integration of every team member expertise from the initial stages of project development to delivery. However, with the historic focus on construction activities, lean implementation remains limited during design and does not always benefit from BIM, nor from the integrated project delivery method (B2, B3).
- The emerging more collaborative and integrated project delivery methods like Bid-Build or Integrated project delivery provide increase of efficiency of communication and collaboration, improved time, costs, and waste control. With such approaches, teams, technology, and processes are integrated into a holistic system and focused on a shared goal. However, such approaches present challenges due to their complexity and need for the development of relevant regulations, as well as of workflow structuring, collaboration environment and a shift from the common practices. Furthermore, it relies on the use of digital tools like BIM and interactive mediums for design and decision-making (B2).

- 4D BIM has a variety of uses, and it represents a useful medium not only for project design, but for construction simulations, analysis, management, and decision-making at any project phase. However, the use of 4D BIM for collective planning and decision-making remains limited for several reasons. First, it does so due to the nature of 4D information that makes it hard to visualize the complex information and to interact with it efficiently. Second, due to the suboptimal professional skills for the adoption of a paradigm shift towards more collaborative work. Third, due to the lack of methods and tools to enable or enhance the use of 4D BIM for collaboration and decision-making (B1).
- BIM, Lean construction, and Integrated delivery approaches benefit from the joint implementation and complete each other. In addition, they all value efficient collaboration as an essential activity to project success. Such implementation operates as the combination of ideas representing people - IPD, processes – Lean construction, and tools - BIM. However, there is the lack of a holistic approach enabling their optimal synergy. Despite dynamic development, the synergy-supporting tools, methods, and frameworks remain limited. 4D BIM and Lean construction tools for collaborative planning to assist integrated team remain limited as well (B1-3).

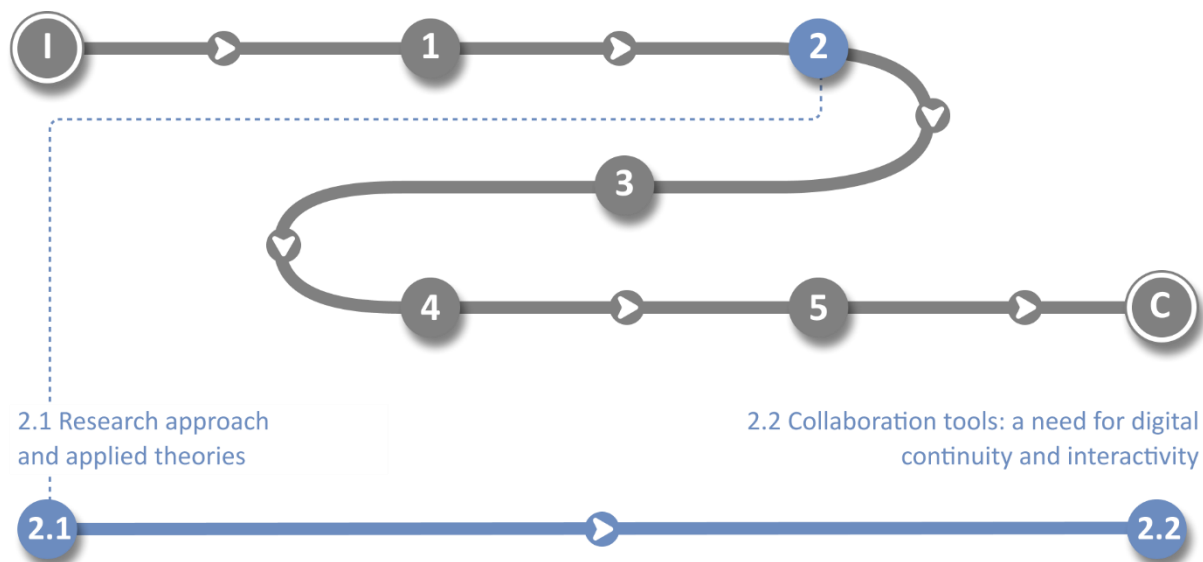
Chapter 2.

Research method and identification of requirements for 4D-based collaboration

The previous chapter portrayed the research context uniting various approaches and their concepts. The current chapter continues to outline the elements of the context with an emphasis on a review of BIM/4D collaboration tools and collaboration interactions. The review identifies several requirements for efficient and integrated multidisciplinary collaboration, with the focus on collective decision-making using BIM/4D and Lean construction principles.

First, the chapter summarizes the elements of context and outlines research questions. Further, it presents the research methods, steps and limitations, and introduces the use of socio-technical systems theory, the activity theory design and user-centered design (2.1).

Second, the chapter outlines the need for digital data continuity and existing practices accessibility and examples of tools enabling collaboration with 4D BIM and Lean approaches, and then it identifies the requirements for contributing to a proposal of 4D-based collaboration scenarios and a prototype (2.2).



2.1 Research method and applied theories

2.1

2.2

The current section outlines our approach to the research and emphasizes its aims. First, the section summarizes the elements of the research scope as they establish the broad context, and it outlines research questions, followed by a description of the research methods, steps and limitations (2.1.1). Second, the section introduces the use of socio-technical systems theory, activity theory design and user-centered design and concludes with an outline of their application to our research (2.1.1,2.1.2).

2.1.1 Research approach outline

2.1.1.1 Outline of the research scope and questions

Scope and barriers

This research in the domain of Architecture, Engineering and Construction (AEC) primarily focuses on the areas of Building Information Modeling/Management and Multidisciplinary Collaboration, and it also extends to Project management and Construction management. A synergy of these areas shapes the research context of BIM, Integrated Project Delivery and Lean construction approaches. Secondly, this research converges with the domain of Human Computer Interaction (HCI) and User-centered design (UCD) approach.

Within the research scope we *explore a digital approach for co-located synchronous collaboration mediated by digital interactive tools and innovative project delivery methods. The collective use of 4D BIM and Lean planning for decision-making is the study object.* The aim is to improve the collaboration quality for AEC professionals, who would benefit from a development of efficient tools, protocols and processes.

First, the research outlines and identifies the existing problems, as we examine the context of recent advancements in BIM, Lean construction, Integrated Project Delivery approaches, BIM/4D uses and their impact on collaboration (Chapter 1). From a broad perspective, there are issues related to each approach implementation and to their joint implementation, such as lack of synergetic implementation experience, established practices, protocols, skills and tools. The raised questions of how these approaches may be implemented together in a beneficial way. From the perspective focused on the project meetings, there are issues related to collaboration efficiency and use of BIM/4D, which are also joint with the issues of quality interactions of the project team members. This raises a variety of questions, such as:

- *How to avoid disruption of the digital dataflow during the meetings and support BIM/4D continuous and accessible to all dataflows?*
- *How to foster integrated team collaboration?*
- *How to optimize the multi-disciplinary multi-user collaboration tools and environment to foster clarity and interactivity?*
- *How to create an environment which adjusts to a specific meeting, phase, actors, and process?*
- *How to foster and benefit from 4D BIM use and implement it as a mediator?*
- *How to present the team members with an access and easy interactions with nD?*

These questions guided the establishment of the research approach, and influenced the research questions, which are emphasized further.

The research proceeds as applied, since its main scope addresses mostly practical problems, some elements of theoretical research contribute to the body knowledge as well. Also, the process is aligned with pragmatism research philosophy with the emphasis on the research aim, the use of mixed research methods and prototype development. However, it integrates the positivist and interpretivist points of view and methods, when they are relevant, which are typical for Management and HCI research areas. An important part of the work is an exploratory research investigation on 4D BIM, Lean planning and construction, and on synchronous co-located collaboration mediated with interactive digital tools through experiments analysis and literature review. However, the findings may provide useful tools for decision-making in a practical scope, and body of knowledge development, rather than as conclusive research.

Issuing from the literature review (Chapter 1; Section 2.2) and supported by the further experimentations, these barriers were emphasized to guide our research:

- *Barrier 1 (B1). Limited BIM and 4D use for decision-making and co-located synchronous collaboration.*
- *Barrier 2 (B2). Need for efficient time management and integrated collaboration, with continuous data and workflow, relevant data visualization and interactions.*
- *Barrier 3 (B3). Lack of synergy in approaches, Lean construction tools have not yet fully emerged with BIM to enable digital collaboration for an integrated team.*

Research questions

This research investigation considers the *technology, people and processes perspective* on BIM, Lean construction and Integrated project delivery implementation, as a comprehensive approach, enhancing multidisciplinary *collaboration and integration, fostering BIM and Lean tools implementation*, with potential for mediation with interactive collaboration solutions. The research guiding questions are resumed by following:

- *RQ1. How does the shift of paradigm by the innovative approaches to project design, construction, and management influences the social and technical aspects of BIM-based collaboration of AEC professionals at the project review and planning meetings ?*
- *RQ2. What is an influence of an implementation of a natural user interactions mediator^{vii}, for collaboration of AEC professionals at the project review and planning meetings, their interactions and the project visualization quality?*
- *RQ3. What are the requirements for multidisciplinary collaborative use of digital project documents and 4D BIM by AEC professionals at the project planning meetings?*
- *RQ4. What are the requirements and implications of 4D BIM and lean scheduling joint implementation for collaboration of AEC professionals at the project planning meetings?*

2.1.1.2 Research theories and steps

Combining Socio-technical, Activity and User-centered design theories

Most of the researchers are concerned with the existing problems in their domains, but they also seek to push the frontiers of knowledge. Miettinen and Paavola outline that the novel technologies “... are naturally future-oriented and try to change reality, improve technology-mediated practices, and create new opportunities.” (Miettinen and Paavola, 2014). Thus, our research proposes the digital

^{vii} A touch table enabling collective synchronous interactions with collaboration software

approach to AEC synchronous collaboration to address the abovementioned questions, and our study blends several theories (Figure 20), which allow to model macro, mezzo and micro levels of abstraction.

The broadest macro level relies on *Socio-technical systems theory*, which allows to describe the collaboration context (2.1.2.1), the relations of the technical and digital, as well as to consider the complexity of the BIM and IPD, of the interactions of the technical, social and contextual aspects. However, to continue the modeling of collaboration activities, STS must be combined with other theories. A study by Baxter and Sommerville analyses the existing approaches to Socio-technical systems design and their relevance to different phases of the systems engineering life cycle. It outlines that even cognitive system engineering and human-centered design do support analysis, design, and evaluation, yet they do not provide the necessary methods and tools to guide the design of novel tools more adapted to the users' needs. Also, Baxter and Sommerville see STS limitations in *Inconsistent terminology, conflicting value systems, various levels of abstraction and lack of agreed success criteria* (Baxter and Sommerville, 2011).

Thus, on the mezzo level, *Activity theory* (2.1.2.1) allows to model interactions between actors, mediators and objectives in the context of the work community, rules and practices. Thus, it allows to address the collaboration situations studies and to model the activities.

However, to continue address the questions, we implement User-Centered Design (UCD). Rogers reviews the awareness of various frameworks and theories by the HCI community at the time. The study emphasizes that the Activity theory "... cannot provide prescriptive guidance in the sense of telling a designer what and how to do design" and outlines the *need for further advancement of theoretical works* to assist with both research and interaction design (Rogers, 2004). In addition, Baxter and Sommerville outline that UCD presents an opportunity to *encompass synchronous development of digital systems and organizational processes*, to use prototyping as a method of *gathering user feedback for further implementation* into the design (Baxter and Sommerville, 2011). UCD methods of user integration and exploration-exploitation are discussed, tested and validated concepts in the literature; yet there is the lack of UCD implementation with organizational theory (Chochoiek, 2017).

Therefore, on the more focused on the digital tools use and user activities and interactions level, *UCD* (2.1.2.2) provides a methodology to describe the collaboration scenarios with the mediators, to design and evaluate a prototype considering the requirements, efficiency and usability.

A more detailed outline of the theoretical concepts is presented further in 2.1.2, as well as an emphasis of their use for BIM and AEC collaboration studies in 2.1.2.3.

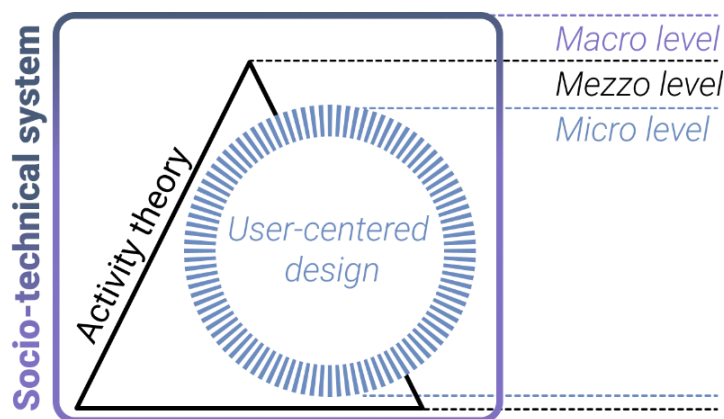


Figure 20 Combination of Socio-technical system, Activity theory and User-centered design for our research

Exploration with analysis, experimentation and proposal prototyping steps

A few research steps were taken by us which included the exploration encompassing literature review (S1) and experiment steps (S2), and the proposal encompassing the step of collaboration personas^{viii} and scenarios proposal (S3) and concluding with prototyping design and evaluation (S4) (Figure 21).

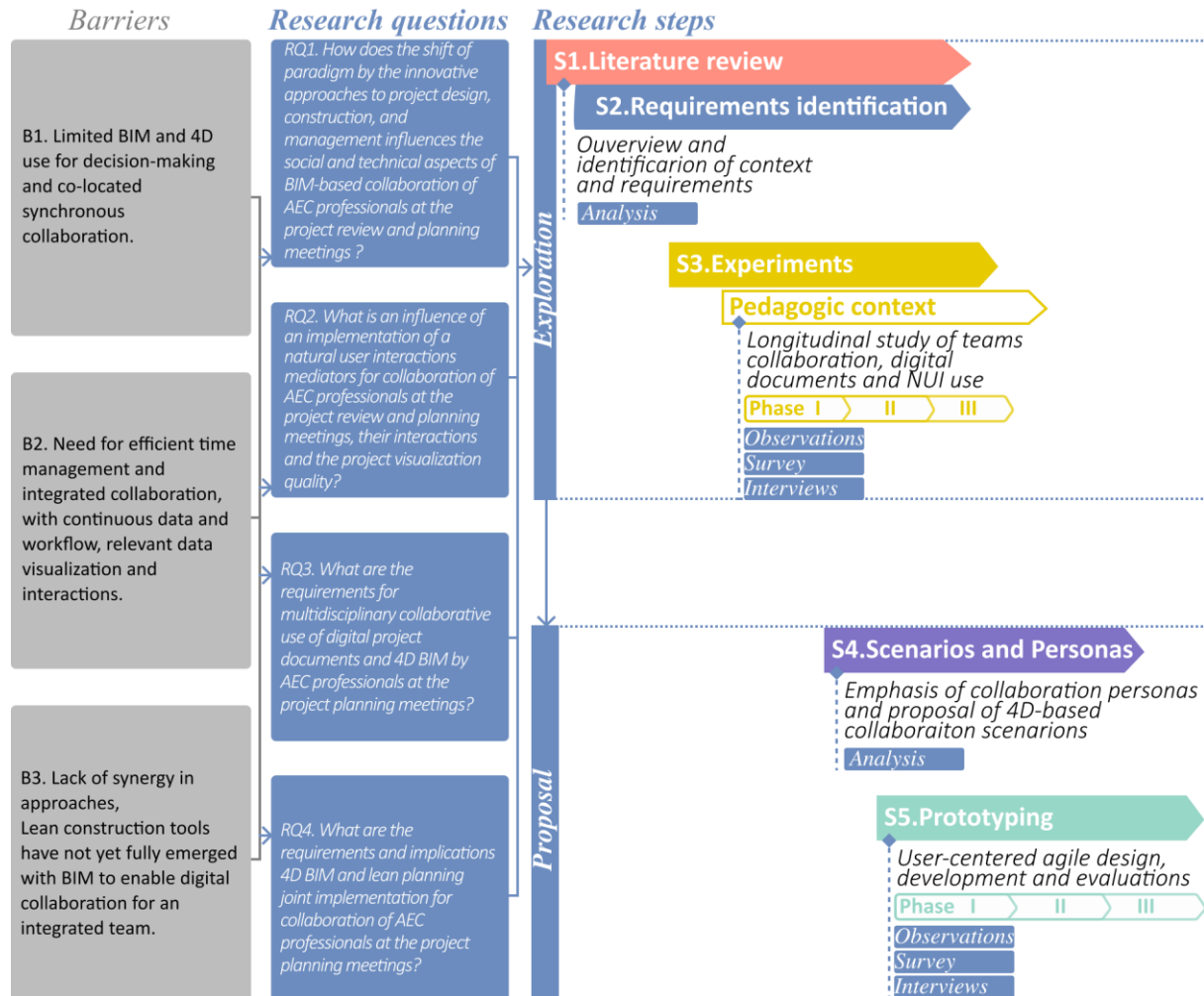


Figure 21 Schema of the research questions, steps and results summary

The research first proceeded with the literature review to examine the context of digital era advancements in BIM, Lean construction and Integrated project delivery methods, and their impact on the social and technical aspects of BIM-based collaboration. Following the context outline, we examine the existing solutions for synchronous collaboration, for BIM and 4D BIM-based interactions, as well as Lean construction planning tools to identify the benefits and future requirements for 4D-based collaborative solution for collective decision-making. The requirements identified from the literature review, for a tool supporting 4D BIM and Lean planning collective use for decision-making (2.2.2), which are identified and further listed in categories corresponding to our study levels:

- Social: processes, organization, rules and context
- Technical and social: digital collaboration environment setting

^{viii} “[c]ollaboration personae are empirically derived descriptions of hypothetical groups of people with specific qualities, goals and needs.” (Judge et al., 2012).

- *Technical: BIM/4D and Lean planning use for collaboration*

To continue the requirements exploration and to understand the activities occurring during project meetings mediated by the digital supports with natural user interfaces with experiments. We run extended in time study of team collaboration within a pedagogical environment. The mixed research methods of observation, survey and interviews allowed to collect qualitative and quantitative data.

As we identify the requirements for 4D-based collaborative solution for collective decision-making, we then propose and evaluate a solution providing an easy access to relevant digital project information for every project team member through collaboration scenarios and *4D Lean board prototype*.

In addition to the outlined research questions guiding the research, the experiments (Chapter 3) and prototyping (Chapters 4 and 5) investigations evaluated the hypothesis, associated with these questions. This research investigation considers the *technology, people and process* dimensions of BIM, Lean construction and Integrated project delivery implementation as a comprehensive approach (Figure 2, p.7), enhancing multidisciplinary *collaboration and integration, fostering BIM and Lean tools implementation*, where the preliminary hypothesis can be resumed by following:

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team.*
- *H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration.*
- *H3. A digital tool uniting BIM 4D and Lean scheduling creates a basis for integration of design and construction dataflows, and is perceived by the users as providing relevant level of information detail for collective decision-making at every phase.*

Thus, the research further develops collaboration scenarios and tools encompassing a prototype in a digital collaboration environment with a multi-user digital interaction interface, which will complete a digital continuity of project documents at decision-making sessions, with an aim to keep the same BIM model in the center of discussions as in the center of design development and to avoid printing documents. The solution aims to avoid incorrect interpretation and loss of information. For users' comfort and collaboration quality it is important to offer the best usability and relevant interactions.

2.1.1.3 Research limitations and reliability

Limitations

This research was conducted without targeting any geographic or regulatory context of the design and construction, but it took a more unattached perspective with the focus on people collaboration and advancing the prototyping. However, the specifics of every construction project such as its program and location, legal context and the choice of managerial approach will still define most of the details about the project's design and construction, collaboration, and management. *Despite the relatively unattached perspective*, it should be also noted that the research was *conducted in France and Luxembourg*.

The chosen data collection *methods were adapted to the research context and to the opportunities which presented themselves*, such as the experiments and evaluation sessions with a limited number of participants. However, more conclusive and statistics-based results on collaboration description and user requirements may be achieved with a *more extended sample size* for observations and evaluations of the synchronous collaboration and of the 4D BIM use.

The latest prompt development of digital technologies and tools unavoidably finds many implementations in AEC. Such as the use of common software and data storage by the project team, or use of Augmented or Mixed reality for construction administration. The current research *focused on the use of a touch table* as activity mediator at the decision-making meetings (collaboration sessions), and not for design or construction visits. A touch table offers easy to understand, *natural user interactions in a group* and in the same and shared environment. Thus, the focus of the research was on the exploration of the benefits from such interactions and environment, in spite of the common use of individual tablets. Such tablets even when connected do not enable group interactions since their interface targets one user.

The specification of the chosen research aims have naturally provided limitations to our scope. For example, this research did not explore the requirements for distant synchronous collaboration or use of other than 3D and 4D BIM dimensions. However, both would be within the range of the future research, since *scheduling is closely related to cost management* it is important to find an efficient way to visualize them together with the 3D and follow up with the use of nD or Digital twins.

Khanzadi et al. use Promise Theory point of view, which “... *advocates decentralization and forming a network of localized components, connected to each other in a chain of promises*” to identify the possible benefits for LPS® task assignment procedure and reinforce decentralized decision-making or self-organization (Khanzadi et al., 2019). This view seeks to implement inspirations from SCRUM to LPS®. Despite the utility of such methods as a source of learning and improvement, their implementation for design and construction projects is out of scope of our study.

Even though *IPD metrics of efficiency and continuous* learning represent an important part of the integrated work process, their integration into the prototyping was not included into the scope. IPD approach creates a structure for collaboration, and in our research, it gives a more comprehensive context to the studies, since the *open and direct communication* together with the *collaborative innovation and decision-making* are the principles of IPD. Thus with the IPD method implementation there is a need to facilitate establishment of these practices in a team and to enhance easy exchange of ideas, and the *need for identification of the project team member roles* to ensure necessary qualifications (AIA, 2007). Integration challenges come from the financial and organizational impacts, as well as that team members come from different work environments thus the professionals need to recreate a common work culture (Fischer et al., 2017; Ch.13), which were not specific to our research opportunities. Also, even with the part of project team willing to implement IPD, there are difficulties in finding the AEC professionals experienced in integrated delivery approaches.

Moreover, many aspects such as the legal structure of IPD contracts or the production process related aspects, despite being critical to the IPD approach successful implementation, are out of our studies' scope. Yet, it is important to highlight that usually traditional construction contracts optimize individual performance rather than establish a legal frame fostering group performance, whereas an IPD contract proposes to share risks, and: “*The parties, through joint collaboration, extend the principles in the IPD contract by developing collaborative work plans, co-location plans, building information modeling (BIM) execution plans, and similar detailed elaborations to the contract structure* (Fischer et al., 2017; Ch16).

Reliability and validity

The use of mixed research methods influences the validity and reliability, credibility and trustworthiness assessment of our study. The mixed methods are beneficial for the better

understanding of our research subject, yet the study faces the issues of the internal integration and legitimation of such mixed methods (Onwuegbuzie and Johnson, 2006). While studying BIM-based collaboration, we compare the results between qualitative and quantitative methods. Their applicability to the general collaboration problems is considered as well.

The experiments described in Chapter 3 implement mixed methods, allowing to assess various aspects of the collaboration. The choice of the participants allowed to gather the information from different participant profiles collaborating in groups, and the same choice of different user profiles was consistent with the prototype evaluations described in Chapter 5. Moreover, all the participants were offered to evaluate the usability and usefulness of the digital tools used as mediums for collaboration, with the UCD quantitative tools, and compared with the qualitative feedback. The usefulness of the emphasized BIM-based collaboration situations and the technological requirements are evaluated with their relevance to the identified barriers (B1-3). In addition, they were compared to emphasized requirements for the digitally mediated synchronous co-located collaboration process. The prototyping results issue from an iterative development affirm the reliability through the internal consistency. The prototype evaluation study was designed to make use of UCD variables to address any concerns of internal validity. The study does not present claims of external validity on the industry level.

Key points of 2.1.1

Research method and applied theories

- Our digital approach to collaboration explores co-located synchronous collaboration mediated by digital interactive tools and innovative project delivery methods, within the broader context of Building Information modeling/Management, Lean construction and Integrated Project delivery. It portrays and articulates the technological and social requirements 4D BIM and Lean planning collective use for decision-making, formalizing it with Socio-technical systems and Activity Theory, and implementing User-Centered Design for analysis and prototyping. The overall aim is to improve the collaboration quality for AEC professionals, who would benefit from a development of efficient tools and processes.
- Our research limitations do not allow to extend the investigation beyond the studies of synchronous collaboration sessions to include the important issues related to the project dataflows, and in particular processes related to data input and output, to particular legal frameworks or BIM protocols. The scope does not encompass the construction production activities in detail, nor seeks to produce a fully operational commercial solution. The distant collaboration role is considered as important for the project development but did not become an object of investigation either.

2.1.2 Approaches and theories for studying collaboration with digital tools

The following section describes the main concepts of Socio-Technical Systems and Activity Theory, and outlines the approaches to Human-computer interactions studies with an emphasis on User-centered design (2.1.2.1, 2.1.2.2). Further, it summarizes the implementation of the concepts and tools to BIM and collaboration studies (2.1.2.3).

2.1.2.1 Socio-technical system and Activity theory as approaches to studying collaborative interactions with mediating tools

Socio-technical system theory summary

An adoption of advanced technology may still provide negative or insufficient impact on collaboration quality or on work outcomes, as the adoption of new business practices and related processes in addition to the technology adoption is required to create an efficient Socio-Technical System (STS). Thus, the technological and social subsystems must interact, adapt, and grow together. Following such advancements, the approaches to design of technologies and relevant practices must evolve to follow the progress as well.

The idea of ***joint optimization and balance*** is in the core of STS. The technological impact on society and the social influence on technology are interdependent, besides the technical development is still a social process as it represents an equivalent to social change (Ropohl, 1999). However, due to the nature of the subsystems, the technical may be modeled and ***designed as modeled in precise way***, but the ***social are rather approximate and are continuously adapting*** mode (Figure 22). Such characteristics must be considered during the research and during the design.

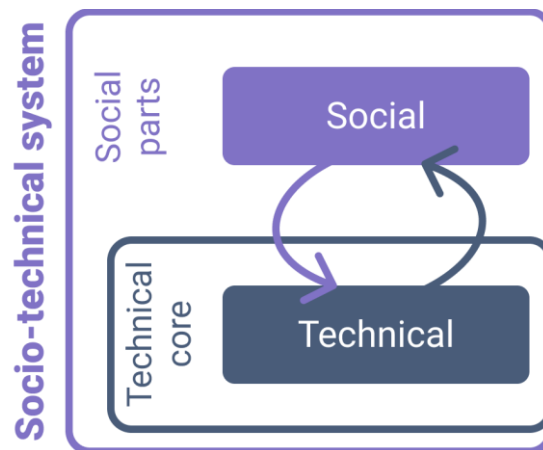


Figure 22 Socio-technical system: Technical subsystem, social subsystem schema

After the emergence in the middle of the XXth century, the STS had decades of establishment and wider implementation in the 1980s. Günter Ropohl reviews the philosophy of STS, and seeks to outline a theoretical point of interdisciplinary integration through a realistic philosophy. In the studies he considers ***a system as a cognitive map of reality***, following the views of general systems theory (Ropohl, 1999). Such approach allows to inherit the assumptions of general systems theory, yet to describe further with the use of systems model: social and technical phenomena, persons, and machines. In

addition, the open systems theory concepts and ideas also provided a basis for STS. Recent studies highlight a *need for more contemporary socio-technical analysis* in correlation with the digital technological advancements and needs for sustainability (Bednar and Welch, 2020).

Various research efforts were conducted to emphasize STS design principles, aside the joint optimization. Their focus was either on more precise description, design, or evaluation of the systems. For example, Cherns emphasized the following STS design principles:

- *compatibility (the design process of STS should be compatible with the objectives);*
- *minimal critical specification (assessment of the essence of the STS and not specify more than required);*
- *variance control (assessment of the social and technical variances, and control in an independent way by the work units);*
- *boundary location (boundaries allow sharing of the knowledge and skills between STS teams);*
- *information flow (adaptation of the information system to the work activities);*
- *power and authority (the authority to access to resources should be granted to the resources direct users);*
- *multifunctionality (actors must be provided with means to perform multiple tasks);*
- *support congruence (not only technical but also social support should be available to the actors);*
- *transitional organization (continuous redesign and adaptation of the STS);*
- *incompletion or the forth bridge principle (design is an ongoing process) (Cherns., 1987).*

Ropohl argues that STS purpose is to assist with design for *both technical and social aspects of work*, by conceiving object systems for every acting function, and by integrating them into the human acting or working relations, *which would assure a balance of efficiency and humanity* (Ropohl, 1999). Thus, when applying STS modeling to the balance and joint optimization, difference of the nature and need for interactions must be considered. With firm theoretical basis STS today reshapes its place adapting more modern perspective, which is similar, to IPD and BIM seeking to design a system which provides and equilibrium of the social and technical aspects.

The proposed principles provide guidance for describing or designing, and outline various important aspects relevant to STS modeling. In further efforts to outline the principles, Christopher Clegg focuses on successful collaboration as a team in STS from a macro perspective. He emphasizes the STS design levels:

- *meta encompassing world view of design,*
- *content focusing on specific aspects,*
- *process guiding the design process.*

These levels include *a large number of principles* (see Clegg, 2000), and proposes as well a list of criteria to guide the STS design and a list of *preconditions for successful teamwork*. Such approach provides a basis for teamwork analysis and adapted STS design. Despite the detailed description and attempts to provide design methodology guidelines, the approach yet does not consider multidisciplinary teams, since it operates on a level of “organization.” In a way an IPD team is united by the same goals and shared motivations, yet it does not have the same homogeneity as one organization. Moreover, the approach does not account for specifics of multidisciplinary and multipurpose settings, nor digital advancements. Further, Badham and Ehn outline that a particular difficulty of STS design is partially a problem coming from its nature focused rather on a single system, in which outline of “... *interdisciplinary grouping is difficult and controversial.*” (Badham and Ehn, 2000).

The design of socio-technical systems encompasses social and technical factors to design functionality, and efficient usage of digital tools. Badham and Ehn suggest that design should be considered as a *social, political, and aesthetic process*. Such approach highlights an importance of aesthetics, rarely perceived outside the user feedback scales, as well as an importance of the quality STS design on a level encompassing politics as a basis of decision-making. Badham and Ehn also suggest that design must issue *from “collective designers”* efforts analyzing technical aspects, communication, collaboration, and negotiation (Badham and Ehn, 2000). Badham and Ehn outline that workplace innovation design emerges from *scientific, social science, technical and user studies* (Badham and Ehn, 2000) (Figure 23).

As highlight Baxter and Sommerville, STS typically focuses on organization processes and structure, however, due to the fragmented nature of the AEC industry and multidisciplinary of a project team with a number of design and construction companies working together, the approach to their study may not be limited to a single “organization” view. Yet, there is still a place for humanistic ideas of STS, as suggest Baxter and Sommerville “... *there is a strong pragmatic case for applying socio-technical approaches to systems engineering*” (Baxter and Sommerville, 2011). Baxter and Sommerville review the design methods and propose an approach of Socio-technical systems engineering serving as a bridge between the system development and the change processes. The idea seeks to improve coordination and the quality of work of the development team through *a better communication of the issues which would impact the design decisions*, and for the “change team” to outline and to conduct the changes implementation.

Further, Davis et al. seek to expand and adapt the theory to the modern digital era and more comprehensive than industrial era systems modeling, and proposes a socio-technical framework to represent organizational systems as the hexagon using six interrelated elements: Culture, Goals, Buildings/infrastructure, Technology, Processes/procedures, People; and consider their environment as well (Figure 24). They outline this proposal as “... *an attempt to provide a simple yet powerful representation of the interdependent nature of work systems, providing a framework for analyzing the linkages and relationships between the different social and technical aspects*” (Davis et al., 2014). Such representation indeed provides the list of organizational elements, and considers the external factors influence, with the main application of general conceptualization.

Naudé Malan outlines STS emergence and concepts from a perspective for application in engineering, and emphasizes that an *STS is indeterminate by nature which allows design flexibility and experimentation*. The study emphasizes STS design characteristics, which:

- *emerge from the dynamics of interaction with the technology through interfaces,*
- *rely on innovation on all levels from technical to policy changes,*
- *need to be “translated” and transformed through relevant users’ feedback,*
- *rely on reflexivity of the users and the designers (Malan, 2018).*

Thus, with such approach the interactions and interface are not mere basis “tools,” but they foster the dynamics in STS, much like the BIM tools implementation changed the dynamics of AEC project collaboration and brought shifts to usual practices. Furthermore, innovation on all levels corresponds to the needs of an IPD project fostering novel solutions on the technical and the social subsystems. Other listed characteristics emphasizing feedback and reflexivity role are both relevant to the AEC collaboration quality and lean practices, as well as to the implementation of UCD for digital tools design.

As any theory, Socio-technical system theory is bounded by its limitations. Historically, an in initial structure of the theory as a descriptive tool to model systems, however it *does not describe the*

interactions between the subsystems, users, or inside the system, thus as a single way of describing a system it does not provide the tools to model or design the interactions. Also, STS considers technological subsystem and social subsystem; however, an important resource of people (users) often is not considered in the system’s model, which limits the consideration of user interactions and their specific needs. In addition, even though an STS seeks to optimize interactions, to learn from the users, and to evolve, there are no specific tools nor conceptual level to outline collaboration interactions.

Another limitation and advantage of the STS is its complexity, encompassing quite different aspects by nature and use. Usually, STS technical core does not benefit from a high ability to unpredictable situations due to its programmed nature. However, the *social parts on the contrary have a high adaptability* due to the user abilities to improvise and adapt their behavior. Thus, while designing the interactions between these subsystems the designers must consider such limitations. An *iterative and evolving design process* is required to achieve the optimal joint optimization.

Sharing knowledge and collaboration is essential for a BIM/IPD project. A study by Søndergaard et al., investigate knowledge sharing and management in STS systems (Figure 25), and outline that they rely not only on the technical but most of all on the social subsystem (Søndergaard et al., 2007).

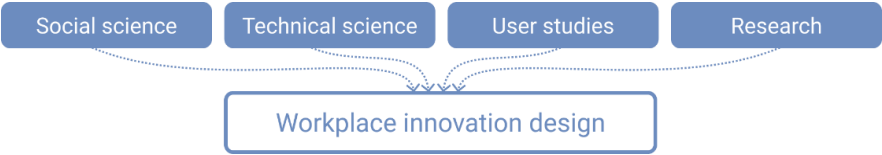


Figure 23 Summary of sciences contributing to workplace innovation design according to (Badham and Ehn, 2000).

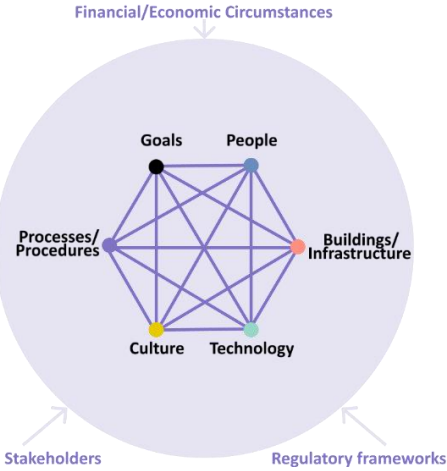


Figure 24 Shema of a Socio-technical system illustrating the interrelated nature of an organizational system, embedded within an external environment (adapted from (Davis et al., 2014))

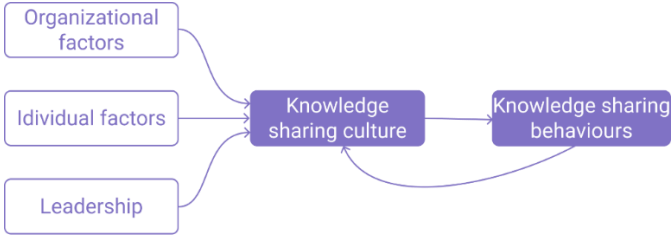


Figure 25 Knowledge sharing framework adapted from (Søndergaard et al., 2007)

Therefore, an efficient STS would *foster such sharing with the social actions*. In addition, Søndergaard et al., observed that *co-location increased knowledge sharing*. When applied to AEC, such observation is similar to the arguments upon benefits of the big room collaboration in IPD approach. Likewise, they outline the need for integration of the collaborating members of the social system into the design of the most relevant to their needs processes and tools. Moreover, *variance control is a key principle of STS* thinking, thus the members must have the ability to independently manage such variance in the system (Søndergaard et al., 2007), which is crucial for efficient design and construction management. The variance as the deviation from the expected performance may occur in the technical subsystem as errors, production problems, workflow issues, or in the social subsystem as lower than expected engagement and poor teamwork (Pasmore et al., 2019).

Regarding the issues of STS use for design, Baxter and Sommerville observe *limited joint implementation of STS and UCD*, where the user would be considered as also a part of the system, and not only as “the user” to a system. However, they mention the efforts of agile and extreme programming, Scrum Dynamic Systems Development Method, which are rather focused on individual users. Thus, these methods do not extend towards a broader socio-technical awareness. Furthermore, unlike early generation of HCI, CMC or CSCW^{ix}, the *UCD explicitly refers to consideration of social and cultural factors*, including working practices and the structure of the organization, which are in the scope of STS (Baxter and Sommerville, 2011). Therefore, their joint implementation may allow to overcome the abovementioned STS limitations.

From more applied to the digital tools design methodological perspective, *STS supports all UCD stages including analysis, design, evaluation of the development* (Baxter and Sommerville, 2011). However, as outline Baxter and Sommerville several levels of abstraction are necessary to emphasize a system, including individual, organizational, contextual. In addition, since STS emerge prior to the HCI emergence and scope on organizations, STS level of detail does not encompass the concepts of “interactions” nor includes the concepts of user profiles, despite the efforts of participatory design method. Furthermore, they outline the limitations of the HCI methods of evaluation focus on an individual using an interface, without consideration of the organization work setting influence on the user behavior (Baxter and Sommerville, 2011).

Moreover not only UCD but the user experience may contribute to building a STS. A study analyzing the modern highly digitalized context outlines that user participation in a STS design is important for STS design, which bring their skills and real work practices into the picture. In addition, the study speculates that in such context the concept of organization becomes increasingly temporary and informal, which fosters changes to the established work practices and by extension to the interactions inside STS (Bednar and Welch, 2020). Furthermore, Bednar and Welch suggest a need for “... a contemporary, open, socio-technical systems perspectives are needed, harnessing appropriate tools and techniques to ensure that systems are created that are meaningful to all engaged actors” (Bednar and Welch, 2020).

In summary, STS allows description of the systems encompassing technology and social aspects of coordination, collaboration, and culture, seeking to provide a balance of the systems and their most efficient interactions. The theory allows us to describe a macro level of BIM-based collaboration. The current limitations of STS design foster implementation of the design methods considering interactions, collaboration and users experience, such as User-centered design.

^{ix} Computer Supported Collaborative Work

Activity theory overview

The modern Activity Theory (AT) implementation occurs in different domains extending from psychology to HCI and organization studies, it is also employed in separate roles and research contexts. According to the outline of Activity Theory use by Clemmensen et al. AT implementation is often combined with other theories, since it provides a broad approach and possibility:

- to describe human activity,
- to adapt the new technologies to activity purpose,
- to formulate design guidelines (Clemmensen et al., 2016).

Since its first outline the Activity Theory (AT) had several generations of development. According to a summary of the AT development history proposed by Engeström and further expanded by Spinuzzi, there are three generations of AT: the first from the works of Vygotsky, the second from the works of Leontiev, and from the works of Engeström (Engeström, 1999). In addition, today there is a tendency of the development towards the fourth generation of AT (Spinuzzi, 2020). However, the development is not linear, but it's so called generations are rather addressing different problems and different fields (Spinuzzi, 2020) (Figure 26).

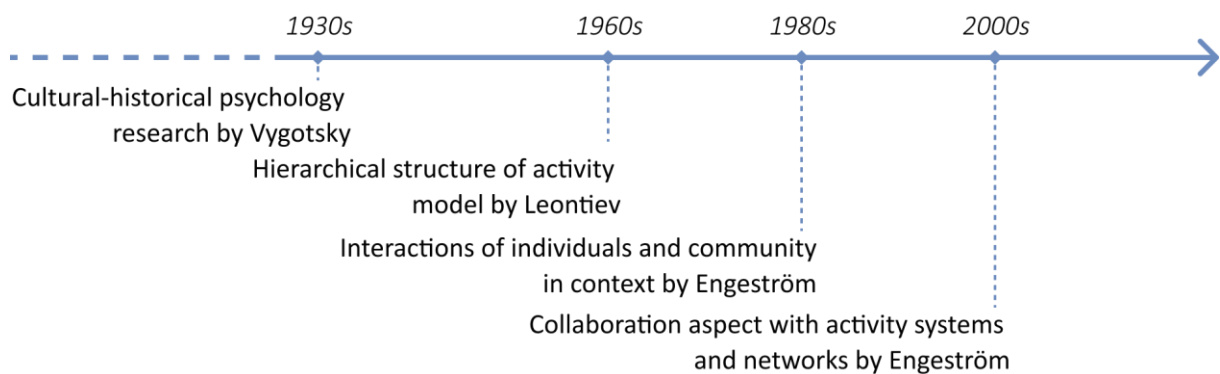


Figure 27 Sequence of Activity theory concepts emergence

An understanding of these generations allows for deeper understanding of the roots of the theory and an evolution of the vision of interactions of the people, place of the mediation artefacts and other elements. In addition, the evolution of the generations is similar to the perception of the HCI through its generations, and it illustrates the need for modeling of complex systems in research.

The foundation of the AT comes from the *cultural-historical psychology* research held in 1930s by Lev Vygotsky. Among other contributions to modern psychology development, Vygotsky introduced the concept of *mediation: a control of actions through physical or abstract tools (artifacts)* (Vygotsky, 1978). Thus, a human interaction with an environment is not direct, but it can be summarized through *a mediation model* which illustrates the relations of *subject, object, and mediating artifact* (Vygotsky, 1978). Such interaction with a specific need or goal of an actor (subject) with the world (object) is an activity. *Contradictions and the mediators*, representing the incoherencies or irregularities, problematic situations in activities' social processes and representing the activity tools, both become indicators of need for change and development of improved activity systems.

The mediating artifacts may be represented by not only physical objects but also abstract phenomena. They mediate among the elements of activity with a design corresponding to their use. Figure 28 illustrates summary of the mediation model elements relations. This model contains only three elements to model an activity, providing the basis for activity modeling.

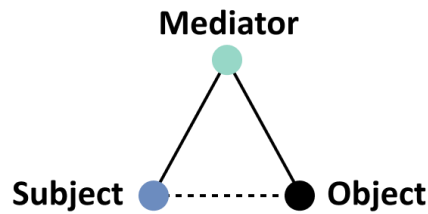


Figure 29 Schema of mediation model according to Vygotsky

Subsequently, in the 1960s the analysis of activity by Aleksei Leontiev argued that an activity brings the *task into the objective reality and transforms it into the subjective one* (Leontiev, 1978). First, Leontiev sees the human mind and activity as inseparable, thus he proposes a *hierarchical structure of activity model*, where on the highest level activities are driven by the object of activity thus its' motives, then on the intermediate the actions are driven by goals, and on the lowest the operations are developed under conditions (Leontiev, 1978). The hierarchy introduction by this approach provides a connection between the work motivations and goals to the actual task.

Seeking to describe not only individual activities, in the scope of a social nature of the mind, Leontiev highlights that there is a difference between an *individual action and collective activity* (Leontiev, 1978)(Leontiev, 2009). Figure 30 illustrates the levels of activity system relation. Yet, the relevance of the levels is not the same for all activities or it may transform, sometimes a top level activity is not the best suited for a description but the lower level action is, according to Preece it is a known problem in AT (Preece et al., 2015).

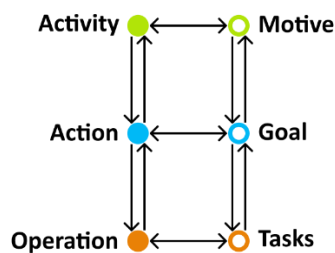


Figure 30 Schema of activity levels relation proposed according to Leontiev

Nevertheless, *an activity is always a social event*, even if it is individual, it still represents a part of a larger context. Thus, the next development of AT by Yrjö Engeström, in a period close to the digital era, introduced a *community component* to the initial subject-object mediational model to encompass the *collaboration aspect with activity systems and networks* (Engeström, 1987) (Figure 31).

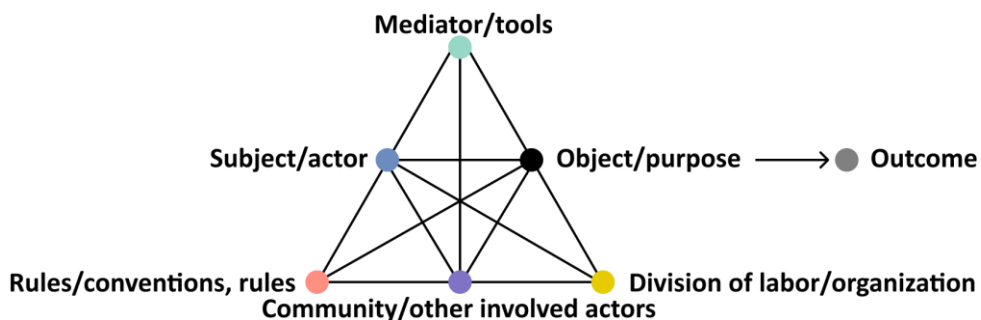


Figure 32 Schema of a structure of activity model proposed by (Engeström, 1987)

Further, the AT was implemented in studies with other domains of application and more empirical research, such as organizational sociology. Sannino describes the organizational sociology “*oriented to the consensus-driven codesign of systems of collective action.*” (Sannino et al., 2009). And with the shift through this approach, the main use of the activity concept is suited for a better ***understanding and modeling of activity systems***, and not just for description. Miettinen et al. outline that during an activity the actor “... *internalizes the means of culture – language, theories, technical artifacts, as well as norms and modes of acting – by participating in common activities with other humans*” (Miettinen et al., 2012).

AT may model actions in a socio-technical system with the following activity system elements:

- *Mediators: tools or concepts used by the actors,*
- *Subject: one or several actors,*
- *Object: the objective or purpose of the activity,*
- *Rules: conventions, rules, guidelines regulating the activities,*
- *Community: social context of all actors,*
- *Division of labor: structure of activity, organization and hierarchy.*

Moreover, Nardi outlines that the activity exists in a work context, but activity itself is the context as well, since “*Context is both internal to people—involving specific objects and goals—and, at the same time, external to people, involving artifacts, other people, specific settings*” (Nardi, 1996).

Thus, AT proposes an epistemological framework to portray human activities and interactions occurring through the mediators in a structured system serving the purpose and influenced by a socially constructed collective practice context, where the activities are the actions of actors aiming to achieve the goal. In our research AT facilitates the description of the mezzo level corresponding to the collaboration session with digital tools, where the actors are the AEC professionals operating as a team who have the object represented by the collaboration goal, and the mediators are the 4D BIM model, collaboration software with natural user interface and touch screens.

AT and HCI

Since AT is focused on mediation, naturally the relationship of actors (human users) with information technologies and associated challenges are in the AT’s scope (Kaptelinin and Nardi, 2018). For example, the AT was introduced to HCI more than 30 years ago, and it outlines the importance of social aspects of technology use.

Bødker proposed an approach which included AT into user interface design. In particular, it presents AT in the ***context of participatory design and analysis of computer system*** (Bødker, 1987). Bødker highlights that people not only interact with technology, but they also ***act through the technology*** (Bødker, 1989), and it illustrates how the adoption of an information system also transforms the activities system.

Bollie Nardi (Nardi, 1996) summarizes the methodological implications of AT and HCI joint use:

- *Research timeframe long enough to understand users' objects,*
- *Attention to broad patterns of activity,*
- *Use of a varied set of data collection techniques,*
- *Commitment to understanding things from users' points of view.*

In addition, from the AT perspective ***the experimentation and continuous learning are essential*** for development of novel tools, solutions and practices (Miettinen and Paavola, 2014). However, as accentuated by Clemmensen et al., AT is descriptive and diagnostic, but not predictive (Clemmensen et al., 2016).

The earlier AT generations of longitudinal ethnographical studies used data gathering methods such as interviews, real life observations and experiments. But the third generation AT implementation for IT development has proved to be useful to analyze the activity and to foster the design process. Preece summarizes that: “*Activity theory provides a framework that focuses analysis around the concept of an activity and helps to identify tensions between the different elements of the system*” (Preece et al., 2015). AT use became common for the HCI domain (Spinuzzi, 2020), and for the iterative design processes (Clemmensen et al., 2016), despite continuous evolution and debates and *lack of a unifying theoretical framework* for all activity aspects applicable to any domain.

Such an approach fosters the *quality of the technology products and design reflexivity* produced by the collaboration at participatory design. AT assists designers with identifying tensions during design evaluations and data interpretation, since it accentuates their focus on relevant user interactions with a system and with each other, while designers analyze not only achievement of an evaluation task, but the user’s attention and engagement actions to perform the task. Also, the users rarely follow all the prescribed steps or plans for the actions when they interact with machines, but the users actions are more often intuitive (Spinuzzi, 2020), therefore the AT approach is useful for qualitative evaluations of users motives and needs.

In our research, we rely on AT as a tool to understand and to guide a domain-oriented design which integrates *the actors* (a project team who become the users of digital tools) and *the mediators* (collaboration tools) into *the activity system* (multidisciplinary collaboration and decision-making). This approach does not yet require us to be experts in AT to benefit the design and development of the tools.

2.1.2.2 HCI and UCD as approaches to study user requirements and design new tools

Interaction with computer research approaches

Since the beginning of the 20th century already ergonomics science has been exploring interactions between humans and other systems integrating physical, cognitive, and organizational parameters. Decades further, following the emergence of personal computers and rapid development of digital tools, various fields, and approaches to studying their interactions with humans have emerged as well. Computers and digital tools use became essential for many domains, work practices and personal tasks of humans, who are referred to as “users.”

An understanding of human behavior is key to the development of *efficient and usable* solutions, and to the quality of user experience. Thus, there is a need for “*people-oriented computers*” (Nickerson, 1969).

Before the rapid development of personal computers, since the 1950-60s the theoretical efforts already were seeking to describe work systems of people interactions with technologies and machines in the work environment. The STS concept was created in the context of labor studies by the Tavistock Institute in London (Emerly and Trist, 1960). However, STS does not provide specific design methods but a philosophical basis for the design (Baxter and Sommerville, 2011). The efforts resulted in various methods and approaches (like Soft Systems Methodology, Cognitive Work Analysis, etc.) describing *the socio-technical systems design* taking into account people (users), tools (machines) and organization (context) (Ritter et al., 2014a). “... technical development, really, means the formation of novel socio-

technical systems” (Ropohl, 1999). Today the STS term is widely used to describe many complex systems.

The field of *HCI* has emerged more than forty years ago, initially encompassing knowledge from *computer science, cognitive science and human factors engineering* for *individual user interaction design with computer applications*. Since then, HCI grew considerably and diversely through three generations of development, with the first focusing on engineering, the second introducing concepts from cognitive science and psychology, and the third including the concepts of user experience and social-cultural context; and it united a large research community.

Next, the field expanded with *Computer Mediated Communication (CMC)* considering the computer as a medium for human communication for work (Bannon, 1992), which is investigating not only the means and processes, but also considering *the nature of collaboration*. Such approach allows to investigate in depth the social dimension, while considering computer as a *part of communication between users*. Further, *Computer Supported Cooperative Work (CSCW)* research field shifted the scope to exploring “... *issues concerning cooperative work arrangements and its support via information technology*” (Bannon, 1992). CSCW designs computer support systems with an approach *encompassing social and organizational practices*. Thus, it extends the investigation to *use of the systems in groups for cooperation and* assists with development of groupware. For example, the use of CAD as an instrument for cooperation is relevant to CSCW subject studies.

The development of design knowledge continued and has progressed during the last three decades. Nowadays there are many approaches to design human-computer interactions (HCI) such as: *User-centered design* (Norman and Draper, 1986), or *Usage-centered design* (Constantine et al., 2003), or *Goal-directed design* (Cooper et al., 2012) or *Human-centered Design and Activity-centered approach* (Norman, 2013). In every approach the design is driven by different concerns. To be more specific, *Human-centered design (HCD)* is defined as: “*the process of ensuring that people’s needs are met, that the resulting product is understandable and usable, that it accomplishes the desired tasks, and that the experience of use is positive and enjoyable.*” (Norman, 2013). And *Interaction design* is “*designing interactive products to support the way people communicate and interact in their everyday and working lives*” (Preece et al., 2015).

For terminological coherence it should be outlined, that the terms “*user-centered*” and “*human-centered*” design are interchangeable, as suggests the World Wide Web Consortium (W3C Web Accessibility initiative, 2004), thus they will be seen as synonyms in our development context. However, in works more related to HCI discipline the first is rather focused on interactions design and the second on a broader interaction process. The technical problems are in the main focus of the user-centeredness rather than the interaction inquiries (Gasson, 2003). All these research and design efforts are still in development. They focus on different aspects but still share a number of concepts. Figure 33 emphasizes the sequence of emergence of the concepts.

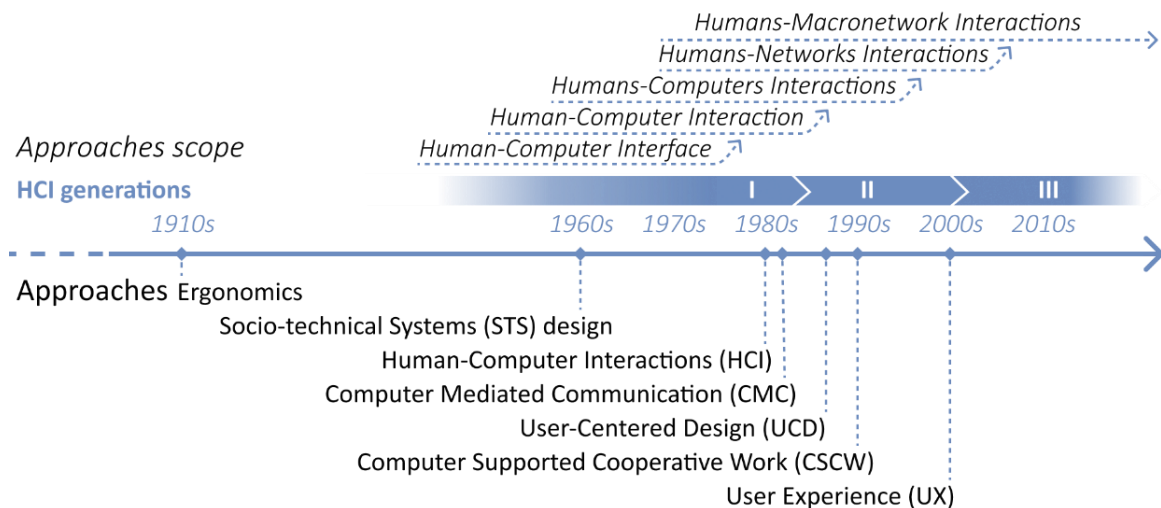


Figure 33. Sequence of approaches emergence to user and computer interactions studies

Usability and user experience in the center of interactions design

The abovementioned approaches continue their development in respective directions. Despite a lack of one unifying theory, these approaches however share an essential principle of the need for a “usability.” A product from a user perspective may be:

- usable – do it easily and naturally, without danger of error, etc.,
- useful – accomplish what is required: play music, cook dinner, format a document,
- used – make people want to use it, be attractive, engaging, fun, etc. (Dix et al., 2004).

Thus, a good product will accumulate the best qualities of its usability and usefulness (Figure 34), and the usage would answer to all the requirements and provide a comfortable use. Usability is also defined as an “Extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use” (ISO, 2019). The simplest model suggests that usability encompasses effectiveness, efficiency, and satisfaction, which could be assessed according to (Bevan et al., 2016) as listed in Table 6.

Yet, usability may encompass different aspects according to ISO 9241, ISO/IEC 25066 or ISO 9126 standards, Nielsen (Nielsen, 1993), (Dix et al., 2004) further extended proposals of Quality in Use Integrated Measurement (QUIM) (Seffah et al., 2006) or specific to mobile devices People At the Centre of Mobile Application Development (PACMAD) (Harrison et al., 2013), and many others presenting different perspectives and focusing on specific studies.

Nielsen (Nielsen, 1993) suggests that usability has a set of attributes: *Learnability, Efficiency, Memorability, Errors, Satisfaction*. Further, Quesenbery seeks to expand the definition from ISO and develops the usability measurement instruments as well, proposing *5Es dimensions* (Table 5) (Quesenbery, 2003) (Quesenbery, 2004).



Figure 35 Usability, Usage and Usefulness in a system with a user

Table 6 Usability effectiveness, efficiency, satisfaction measurement instruments

| Effectiveness | Efficiency | Satisfaction |
|----------------------|-----------------------|---|
| Tasks completed | Task time | Overall satisfaction |
| objectives achieved | Time efficiency | Satisfaction with features |
| Errors in a task | Cost effectiveness | Discretionary usage |
| Tasks with errors | Productive time ratio | Feature utilization |
| Task error intensity | Unnecessary actions | Proportion of users complaining |
| | Fatigue | Proportion of user complains about a particular feature |
| | | User trust |
| | | User pleasure |
| | | Physical comfort |

Table 7 5Es dimensions of usability, design approaches and evaluation techniques (adapted from (Quesenbery, 2004))

| Dimension | User needs | Design approaches | Evaluation Techniques |
|-----------------------|-----------------------------|--|--|
| Effective | Accuracy | <ul style="list-style-type: none"> Provide feedback on all critical actions Eliminate opportunities for error Provide sufficient information for user decisions | <ul style="list-style-type: none"> Create scenarios with difficult or ambiguous tasks Evaluate tasks in terms of how successfully they are completed and how often they produce undetected errors |
| Efficient | Operational speed | <ul style="list-style-type: none"> Design navigation for ideal and alternate workflows Provide shortcuts Use interaction styles and design widgets that support speed Minimize extraneous elements on the screen | <ul style="list-style-type: none"> Construct the test with enough repetitions of typical tasks to create a realistic work rhythm Use working software or a high-fidelity prototype Observe users at work, looking for situations that interrupt them or slow them down Collect timing data, but also interview participants for their subjective impression of the program |
| Engaging | To be drawn in | <ul style="list-style-type: none"> Use clear language and appropriate terminology Set a helpful tone, with a level of conversation suitable for the users Structure functions to match users' tasks | <ul style="list-style-type: none"> Use satisfaction interview questions or surveys as part of the evaluation Do comparative preference testing of presentation design Construct the test so that participants are able to abandon a task if they want |
| Error tolerant | Validation and confirmation | <ul style="list-style-type: none"> Transform "errors" into alternative paths Use controls that aid in accurate selection Be sure actions are easily reversible | <ul style="list-style-type: none"> Construct scenarios to create situations in which errors or other problems are likely Observe how easily or accurately users are able to recover from problems when they occur |
| Easy to learn | Just in time information | <ul style="list-style-type: none"> Make the interface helpful with minimalist prompts and instructions provided where they are needed Create "guided" interfaces for difficult or infrequent tasks | <ul style="list-style-type: none"> Control how much instruction is given to test participants, or recruit participants with different levels of experience or knowledge Mix frequently used tasks with functions used less often or tasks with unusual variations |

However, Bevan et al. review the evolution of usability perception in ISO standards and states that not only measuring the effectiveness, efficiency and satisfaction is important to understand the user experience "effectiveness, efficiency and satisfaction represent the intended outcomes of interaction, but that their measurement does not represent the only way of evaluating usability" (Bevan et al., 2015). Fostering more complex and holistic investigation on users interactions, the approach of User experience considers the system, the user but also the "user's perceptions and responses that result from the use and/or anticipated use of a system, product or service" (ISO, 2019).

Thus, it includes cognitive, socio-cognitive, and affective aspects in addition to usability into the analysis of users' interactions with artifacts reaching out to include:

- hedonic quality (pleasure-producing product qualities),

- *pragmatic quality (user-perceived usability),*
- *beauty (aesthetics),*
- *goodness (overall product quality) (Law and van Schaik, 2010).*

As outline Law and van Schaik “... *the success of digital artefacts is to a large extent positively influenced by the extent to which they promote a high-quality experience in their users*” (Law and van Schaik, 2010). However, as outline Ritter et al., user experience is often assimilated with usability, yet it focuses not only on the efficient means to a task accomplishment, but on the user perception of the use experience. The distinction of user experience and usability requires for more systematic conceptual analysis (Ritter et al., 2014b). The emphasis is subtle, as with all the above listed approaches, but every particular scope results in implementation of different means and strategies to accomplish efficiency and usability.

Currently, the dominating approaches to studying interactions also account for *social and organizational behaviors, multi-modal and context-aware interactions*, as a part of *UCD, Design thinking, User Interface (UI) design and User Experience (UX) design*. Moreover, UCD “... *would consider the processing capabilities of the human user and analyze tasks from the perspective of the user*” (Ritter et al., 2014b), which basically puts the user in an interaction designer position.

Since UCD considers *the technical issues together with social and organizational* issues as part of one system, it follows the similar approach as the Socio-technical system design. Confirming this tendency, Kuutti and Bannon observe the shift of *paradigm towards more practice-based approaches* in HCI (Kuutti and Bannon, 2014). However, despite UCD and UX broad successful implementation by the industry, their focus on more practical usability concerns rather than on conceptual efforts is considered a weakness by some HCI community members, who are choosing general conceptual approaches of distributed cognition, activity theory, situated action, or semiotic engineering (Bannon, 2017).

UCD and design thinking

For the last three decades, there has been a development of tools and experiences design knowledge. Nowadays, a variety of approaches to design human-computer interactions (HCI) is available, such as: *User-centered design* (Norman and Draper, 1986), or *Usage-centered design* (Constantine et al., 2003), or *Goal-directed design* (Cooper et al., 2012) or *Human-centered Design and Activity-centered approach* (Norman, 2013). Within each approach the design is driven by different concerns.

According to Preece, *UCD is based on an early focus on users and tasks, empirical measurement, and iterative cycles design* (Preece et al., 2015). In our context, we focus on the primary users (architects, engineers, contractors, clients, etc.), who are understood as those who would have frequent use of the system during the meetings. The iterative cycle follows the similar to design thinking path, and it repeats in every phase of the design development, and it includes:

- *Specify the context of use,*
- *Specify requirements,*
- *Create design solutions,*
- *Evaluate designs (Figure 37).*

UCD uses a variety of tools to describe and design the user experience, but the main tools are:

- *user personas describing the typical imaginary users of a system,*
- *scenarios portraying the “use-story” of a system by persona,*
- *use-cases illustrating steps of interactions between personas and the world.*

The design becomes one of the instruments to create the novel and efficient interactive digital solutions. To define the purpose of design, Norman highlights that *design must be thought as an experience* and as the *way of interaction between people and technology* (Norman, 2013). Where the experience design puts a *focus on the quality and enjoyment* of the total experience by the users, and the interaction design puts a focus on *users (humans) interaction with technology*.

To implement it successfully, we should be “starting with a good understanding of people and the needs that the design is intended to meet” (Norman, 2013). Thus, the methodology stresses the importance of *involving the real users through the development*, starting with the gathering of most relevant users’ needs and requirements in order to develop the most appropriate. But further, it also highlights that it is equally important to involve the users into the prototype evaluation (Preece et al., 2015), and to choose among alternative designs. UCD proposes to implement both investigative and generative methods. Thus, we have run multiple experimentations and prototype user-tests as described in chapters 3 and 4.

While UCD provides a methodology to improve usability and user experience, a similar approach of Design thinking encompasses the new products creation and expanding further than the interface design with UCD. Through the last decades different discourses have described the *Design thinking* from the point of view of managers, designers, educators and academia (Johansson-Sköldberg et al., 2013). However, the important highlight of all the discussions is that the Design thinking implies *an iterative and expansive design process*. In more detail, first, to explore the design problem the designers proceed with *information gathering* to understand the future users and define their needs. Next, to *explore the solution*, they gather future solutions *ideas and emphasize them as a prototype*, which is finally *assessed* by the users. Such iterative design is well suited for the early design stages and research prototyping; thus, it is well suited for our research context (Figure 367).

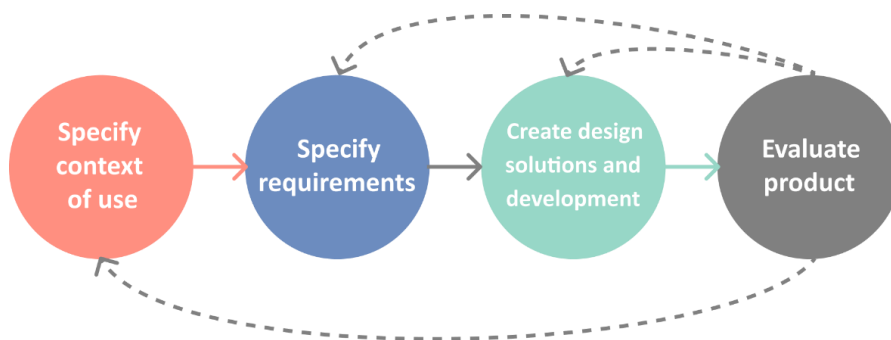


Figure 37 User-centered design steps

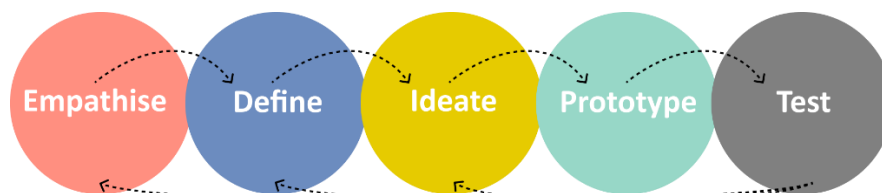


Figure 38 Design thinking process iteration steps

Further, in our prototyping (5.1.1.2) we rely first on design thinking as an approach to *innovative problem solving, as a way to identify user needs and to propose novel solutions*. Additionally, according

to Norman (Norman, 2013), the user-centered design is one of the tools of the Design thinking. Therefore, second, we implement the UCD as an approach that helps *to generate and validate the design proposal*, and *to explore the users' needs* to provide a more effective proposal in the future.

2.1.2.3 Socio-technical and Activity approaches for BIM collaboration studies

STS use for BIM collaboration studies

The global taxonomic review of BIM studies highlights a need for research to adopt a socio-technical perspective (Saka and Chan, 2019). Since the emergence, socio-technical system theory and design became a part of a variety of studies concerning different domains, including AEC industry and BIM domain. Before BIM establishment, Schweber and Harty investigated socio-technical networks analytical tool implementation to construction management research focused on 3D-CAD use. They outline STS as an approach to study innovation and transformation, which *considers the context, actors and artefacts interactions*, and allows for long term *analysis of continuity and change* (Schweber and Harty, 2010). Thus, through such approach the researchers could model the emerging digital tools and practices.

Various authors pursued an idea of describing BIM as a socio-technical system. Harty et al. see *BIM as a socio-technical system of interdependent tools and practices and shaped through the use*, which provides a more holistic approach to investigation, and it allows to study the complex phenomenon of *"socio-technical practices which emerge from implementation and use."* (Harty et al., 2010). The important observation outlines that not only the BIM as technology changes practices, but the practices needs influence the system from the progressive learning and thus shaping the joint optimization.

Further, Mondrup et al. investigated collaboration with BIM, and observed that sometimes technical issues shaped the social practices, and emphasized that *"... sustainable BIM adoption requires an integrated approach, combining technical structures and social practices."* (Mondrup et al., 2012). Thus, despite the complexity of two subsystems, a more holistic approach is required for STS modeling and more integrated for the BIM collaboration and project delivery. Also, the work on interoperability and development of IFC considered the socio-technical process of IFC creation as a part of the process inside an organization, respecting regulations and using BIM software (Laakso and Kiviniemi, 2012). Therefore, not only a dimension of a single organization, but also industry-wide regulations extend to the basis of STS.

As a comprehensive effort seeking practical implementations, Enoch Sackey proposed a *framework for sociotechnical systems analysis of BIM implementation* (Figure 39), which is allowing BIM consistency. The framework allows to assess technical and social issues of BIM implementation in the context of construction organization, provide understanding to policy makers, to assess and analyze a particular constituency (see Sackey, 2014). The study outlines a variety of contextual issues of BIM implication, suggesting that *"... inter-organizational rationality, environmental conditions and how constituents respond to these environments are important antecedents that need to be considered during the implementation efforts."* (Sackey, 2014). The study offered a practical tool and a perspective emphasizing the technical and social elements.

Expanding beyond 3D BIM, a study by Zhou et al. also sees BIM as a socio-technical context for collaboration, but investigates the use of 4D collaborative modeling and reports that it *"... involves*

substantial socio-technical issues from network computing and human–computer interaction” (Zhou et al., 2014). Such approach highlighted a variety of aspects including BIM dimensions, interactions and collaboration subjects, as well as emphasized the need for joint implementation of STS as a broad perspective and HCI design methods. Further, Mikael Tallgren adopted STS extended perspective to investigate how BIM tools aligned to a collaborative planning process. The proposed ***analytical framing is three-dimensional including people, processes and tools***. It is following the studies of BIM and Lean analysis with these dimensions, and the need for user’s roles and actions assessment (Tallgren, 2018). The analytical framing corresponds to modern requirements of STS modeling and advancements of AEC technologies and management approaches.

Another perspective, reaching beyond BIM design and 4D/5D simulations is taken in a study by El-Diraby et al., which materializes a proposal of a BIM-based tool for implementation of ***socio-technical analytics of green buildings as a part of sustainability analysis***, and emphasizes that design of green facilities is a socio-technical domain. The design is supported by shared knowledge and collaboration as social phenomenon but empowered by online BIM workflow (El-Diraby et al., 2017). In this study ***socio-technical approach is a tool empowering collaborative exchanges and sharing of knowledge*** in a system based on BIM workflow.

Li, Greenwood, et al. proposed socio-technical systems methodology for a ***multidimensional framework design listing dimension (political, social, technical), agents, opportunities and challenges***. It assists with portrayal and analysis of Distributed ledger technologies implementation in AEC (Figure 40) (Li, Greenwood, et al., 2019). Such approach extends the dimensions of ***investigation beyond technical and social***, and even aims to integrate processes into the framework in the future. However, the study is focused on blockchain implementation in AEC, and not specifically on collaboration or BIM use.

In summary, Socio-technical systems perspective was adopted by various authors to model interactions between technical tools, such as BIM systems and social practices, such as communication, collaboration, organization, and extended from the “closed environment” to connect with the context, external environment, culture and policies. In addition, with the emergence of integrated practices and synergies of BIM and Lean, additional levels of the STS are required to provide a more holistic view of the system and to include all relevant interactions. Moreover, the joint implementation of STS with HCI methods provides a powerful framework and tools for developing efficient approaches and useful designs

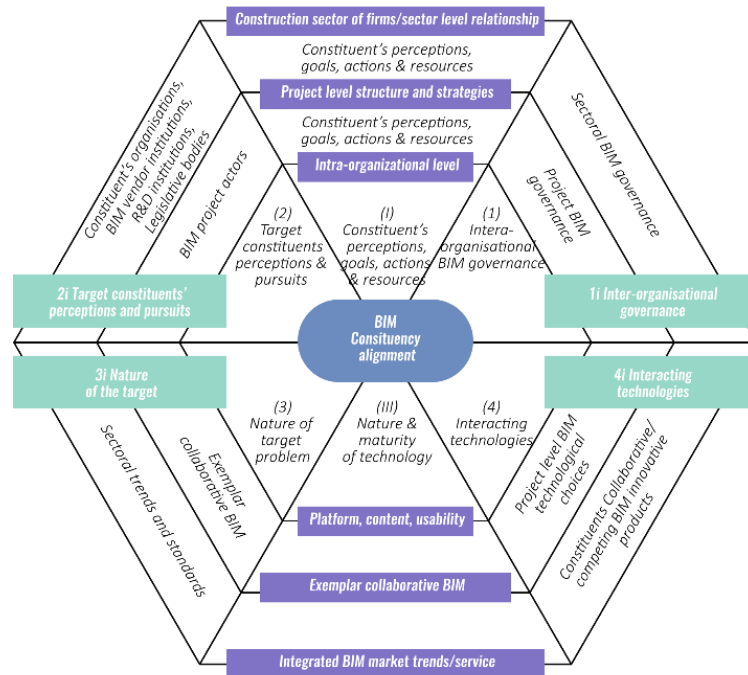


Figure 39 Framework for a sociotechnical systems analysis of BIM implementation (adapted from (Sackey, 2014))

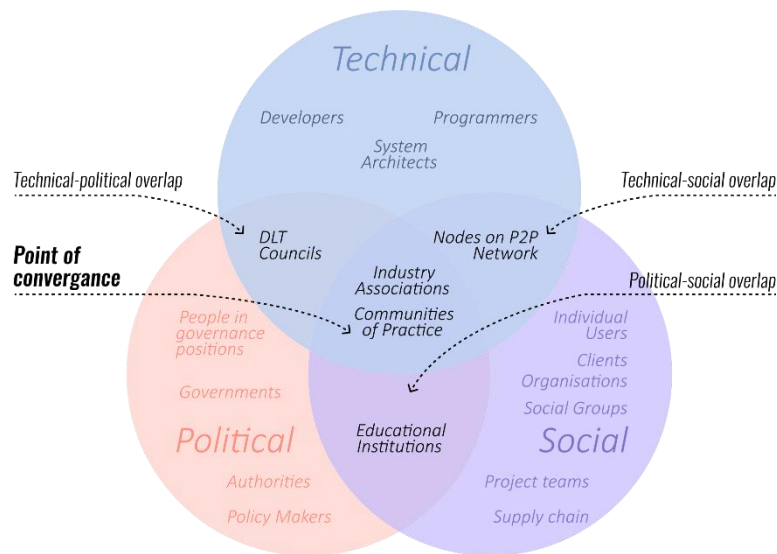


Figure 40 Schema of the multidimensional framework and identified agents for each dimensions, (adapted from (Li, Greenwood, et al., 2019))

AT use for BIM collaboration studies

Emerging integrated practices and BIM implementation were subject to several studies, seeking to describe their interactions with a system encompassing technology, people, processes, context and actions.

As a beginning of discussion on the place of integrated practices, Forgues and Koskela state that relational contracting is essential for value generation. Thus, they investigate collaborative procurement and integrated design impact on the project team performance using AT perspective, since it poposes a ***comprehensive framework focusing on activities*** and not on processes (Forgues and Koskela, 2009). They describe that traditional contracting is not adapted to the needs ***of integrated teams and becomes a source of socio-cognitive problems***, thus there is a need for a change of context of collaboration (Forgues and Koskela, 2009).

Martin and Hartmann investigate the knowledge creation process in construction and applicability of AT to construction management. They suggest that AT may be useful to describe micro level processes, since it allows to ***“... encapsulate the underlying dynamics by linking individuals to the tools they are using, the values and beliefs they are referring to, and the community they are part of.”*** (Martin and Hartmann, 2010); the study also emphasizes, that ***AT enables multi-scale modeling***, thus it may be used to describe the processes on a macro level as well.

Next, Forgues and Iordanova observe that the emergence of BIM and integrated design process approaches challenge the traditional practices as well, but like the integrated teams they need to be formalized. Thus, they continue to rely on AT to resolve socio-technical issues, and propose an ***IDP^x-BIM Framework*** to reshape AEC design practices. They observe a need for project teams ***“... to break the power and knowledge barriers and build a shared mental model”*** (Forgues and Iordanova, 2010), thus they are proposing a process including multiple feedback loops and ***relying on technologies for innovation and knowledge generation***.

Furthermore, to provide a more comprehensive model, the following study by Forgues et al. responds to the need for a framework ***encompassing processes, technological means, normative aspects and domain knowledge*** with an integrated and evolutionary body of knowledge framework. They rely on AT, situated action and boundary objects theories, regarding ***as an activity the social process of learning and knowledge generation*** by AEC project team members (Forgues et al., 2012). Forgues et al. propose scenarios ***“...providing specific information, depending on context and timing”*** (Forgues et al., 2012) which foster collaboration and support the integrated practices.

A study observing the emergence of a more integrated and collaborative project delivery method (approach) of partnering by Hartmann and Bresnen presents an analysis of an approach transforming the usual practices. Since such approach ***“... depends on the individual, organizational and activity-related circumstances of social interaction”*** (Hartmann and Bresnen, 2011), thus adoption of AT perspective ***allows to formalize the mediating role of social practices and emerging tools***, to identify contradictions and cognitive gap fostered by the shifting practices (Hartmann and Bresnen, 2011).

One of the efforts of applying AT to BIM implementation research by Miettinen et al. outlines the ***AEC problem of an “object”*** of AT representing the design and construction project with the set of client's requirements being clear, yet not specifically the same “object” for all project stakeholders due to their specialization and interests; which becomes ***source of errors and incompatibilities “... caused by different expertise, education and special tools will not disappear but remain a key feature of***

^x Integrated design process (IDP)

multidisciplinary work" (Miettinen et al., 2012). Thus, in such system contradictions are inevitable. The introduction of *BIM (new tools) causes the first contradiction fostering changes in the elements of activity like division of labor, rules, and contractual arrangements*. The second contradiction in BIM design models being *"not flexible enough to allow simulations for design alternatives in the early phases of design"*, nor allow easy multidisciplinary use of BIM information for simulations as a mediator for decision-making (Miettinen et al., 2012). Miettinen et al. report that the clash detection lists did not allow integration of simulations for collaboration, and outline the need for development of easy and combined use of multidisciplinary BIM models (Miettinen et al., 2012).

Furthermore, in a following study Miettinen and Paavola seek to understand, analyze and enhance BIM implementation using two alternative frameworks, one being a normative and socio-technical framework, while the other is an activity–theoretical/evolutionary framework (Miettinen and Paavola, 2014). They emphasize the analysis with BIM *"introduced by evolutionary economics – as a new socio-economic paradigm"*, fostering a shift from the fragmented to the integrated approaches (Miettinen and Paavola, 2014), which illustrates again the complementarity of socio-technical approach with AT.

Various studies seek to provide a comprehensive model to describe AEC collaboration and use of BIM tools, more collaborative construction management and project delivery methods. Such modeling often encompasses technology, organization and processes. An additional dimension was proposed in a study by Poirier et al. suggesting a conceptual framework of collaborative project delivery systems where the context dimension assures cognitive and conceptual interoperability, which support understanding, knowledge sharing and common ground (Figure 10). Poirier et al. follow the idea that individual's knowledge is influenced by language, history and culture which shape interaction patterns and behaviour, as suggests the first generation AT from a cultural-historical perspective (Poirier et al., 2014). In the collaboration context the cognitive interoperability supporting knowledge flow occurs on an individual (actors) level, and conceptual interoperability supports work between different disciplines and groups. The study emphasizes that the consensus on meaning of concepts is due to the fragmented structure of AEC which fosters barriers to cognitive interoperability (Poirier et al., 2014). Thus, Poirier et al. highlight that in order to create an optimum collaborative environment the team must align their use of technology, but also assure the interoperability workflows of organization and processes, which directly impact the team members actions (Poirier et al., 2014).

Further investigations of BIM design and collaboration in a study by Nørkjaer Gade et al. analyze as well BIM-based design using AT and seeking a holistic model including, activities, people, interactions and technology, more precisely where the design activity is mediated by the BIM-tools encompassed the individual, social and instrumental entities (Nørkjaer Gade et al., 2019). They identified dilemmas interrupting the activity of a team which contribute to further BIM-tools development enabling use of BIM for: visualizations fostering more efficient design and decision-making, transformations of the building design, facilitation of analysis and evaluation.

Moreover, diverging the research scope from design and construction, a study by Lu et al. analyzes from the AT perspective implementation of BIM for operations and maintenance. They propose a detailed theoretical model encompassing actor and process layers, and *emphasizing 32 contradictions and recommendations* to enhance the evolution of tools and practices (see Lu et al., 2018). One of the findings highlight a need for the *digital and process tools adapted for interdisciplinary* use at various project development phases, presenting *the contradiction between tools and community* (see Lu et al., 2018). Another study encompassing other phases of a life cycle and time management related activities by van den Berg et al., investigates BIM use for deconstruction from AT perspective. It proposes a reorganization of an activity system with BIM based methods to assist with deconstruction activities of

analysing existing conditions, labelling of reusable elements and planning deconstruction with 4D deconstruction simulation (van den Berg et al., 2021).

Therefore, a variety of research efforts presented application of AT to BIM implementation and integrated collaboration encompassing various phases of project development, and exceeding beyond construction delivery to operation and maintenance. Much like UCD, the AT proposes an evolutionary view.

UCD use for BIM/4D and collaboration studies

Previously outlined STS and AT applications to AEC studies proposed frameworks to describe a complex system including technologies and AEC professionals, as well as modeling their interactions, which provided conceptual ideas and system models, yet they propose limited methodological tools to guide the design and development of novel digital tools and interactions. Thus, various studies relied on approaches considering the user as the center of activities and interactions for BIM and collaboration research to propose and prototype the novel tools and systems. A study by Miettinen and Paavola of BIM implementation and outlines that it “... *implies learning by experimenting and invention of novel uses in which process the practitioners and users play a key role*” (Miettinen and Paavola, 2014). Therefore, AEC professionals in addition to being users of technologies and methods, must contribute to the development of novel uses of these technologies and methods. Hence, the feedback from the users is essential for the future tools and processes development.

Some studies implemented concepts relevant to usability improvements or user participation in design. For example, Lee and Jeong proposed *an ontology model and design workspaces for relevant information filtering in design collaboration*, where the user would interact with the 3D project views relevant to his discipline or role, thus define the interface (Lee and Jeong, 2012). The study proposed a complex and multi-level system yet did not implement UCD analytical tools or emphasize the user role in system design further than the source of information visualization requirements.

Chang et al. outline that despite the growth of digital planning and 4D modelling, a successful integration of such tools depends on the effective and efficient use. Thus, they investigated the optimization of color scheme on 4D models with a selection, examination, and user test (SEUT) procedure (Chang et al., 2009). Usability tests were run to assess users’ feedback by allowing the users to define their own requirements combined with 5Es usability framework published (Chang et al., 2009). From the perspective of usability evaluations, the study provided solid arguments and a framework to allow most efficient design choices regarding 4D color scheme and guidelines for future UI design. However, the study did not include planning activity.

Dawood et al. introduced a 4D visual planning tool as a part of the VIRCON system and evaluated the usefulness and usability of the tool. The usability was assessed through experimental sessions with AEC professionals following set up the project and resources phase, space planning phase, analysis and optimization phase, and progress, collisions and special loading visualization phase (Dawood et al., 2005). Such evaluation protocol provided detailed feedback on task perception and allowed to emphasize several conclusions, such as perceived ease of use and high usefulness of the tool, yet some limitations and requirements for the future tools were outlined as well concerning need for interoperability or integration with other tools, need for the users to study the tool, and to foster the UI design.

A study by Tsai et al. presents feedback on 4D tool implementation in a large construction firm using the framework comprising stages of *system evaluation, usability study, and management plan* (Tsai et

al., 2010). The usability tests allowed to gather users’ feedback on 4D tool use, providing the technological and social requirements summary for the management plan proposal for a 4D tool implementation proposal. The approach allowed to investigate not only the use of a 4D tool but also proposed the processes of transformation, yet the usability assessments rely on professional tasks specific to 4D evaluations and time-tracking without UCD analytical tools implementation.

Daniel Zignale proposed an approach of UCD and personas to collaboration tools prototyping, where he outlined the importance of identification of specific to every AEC discipline requirement and validated the importance of practices and uses the prototyping. Thus, the study implemented contextual use-cases to gather user feedback and to foster design and development of the tool (Zignale, 2013). The study concludes with *a diagram of activities for construction administration and* emphasizes the basic requirements for a “Control board” tool and need for interactive displays to mediate such activity.

Zhou et al. report that STS and UCD approaches implementation resulted in a usable 4D CSCW prototype. The users evaluated UI in terms of satisfaction and effectiveness presenting positive feedback on the prototype, 3D navigation, filters and information quality. Also, Zhou et al. outlined that despite the good usability of the tool, the experiments suggest that “... there is a learning curve for construction planners to get acquainted with the model-based planning when they access the collaborative 4D modelling system for construction planning and simulation.” (Zhou et al., 2014). Therefore, future UCD studies must consider this observation to adapt design and user evaluations.

Emphasis of the research framework combining STS, AT and UCD

Thus, our research proposes the digital approach to study the 4D BIM-based synchronous co-located collaboration with digital mediums, which investigates three different aspects. Thus, the research framework combines the constructs and tools from Socio-technical, Activity and User-centered design theories to model macro, mezzo and micro levels of abstraction (Figure 41). On the broad scale we study digitally based collaboration and integration (Figure 42); on more intermediate level we study BIM-based co-located synchronous collaboration and the use of digital mediators use for project meetings (Figure 43); and on the digital tools and interactions level we study 4D BIM and Lean digital tool use for collective project and planning review at the meetings.

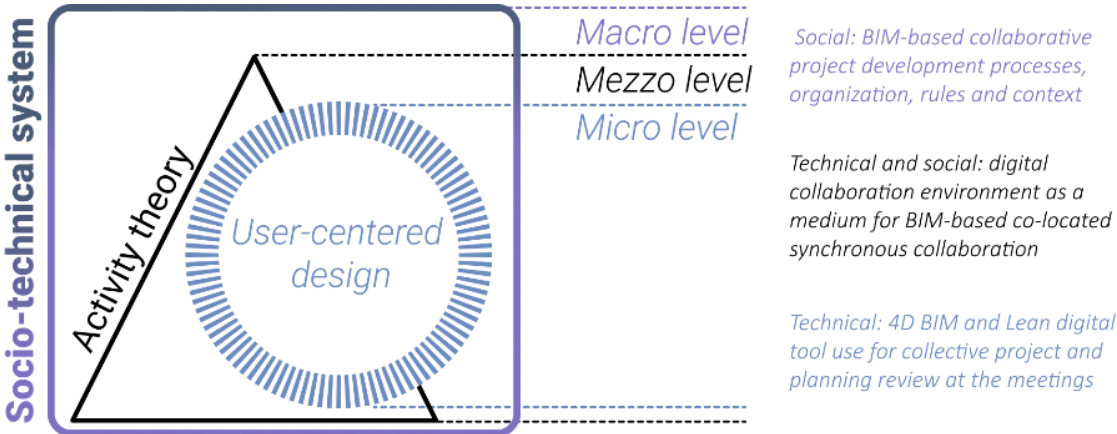


Figure 41 Combination of Socio-technical system, Activity theory and User-centered design for our research

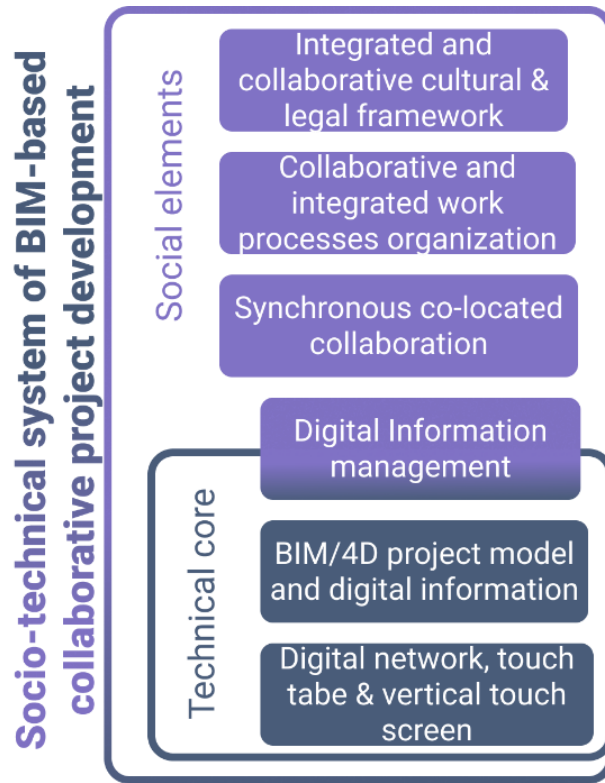


Figure 42 Socio-technical system of BIM-based collaborative project development

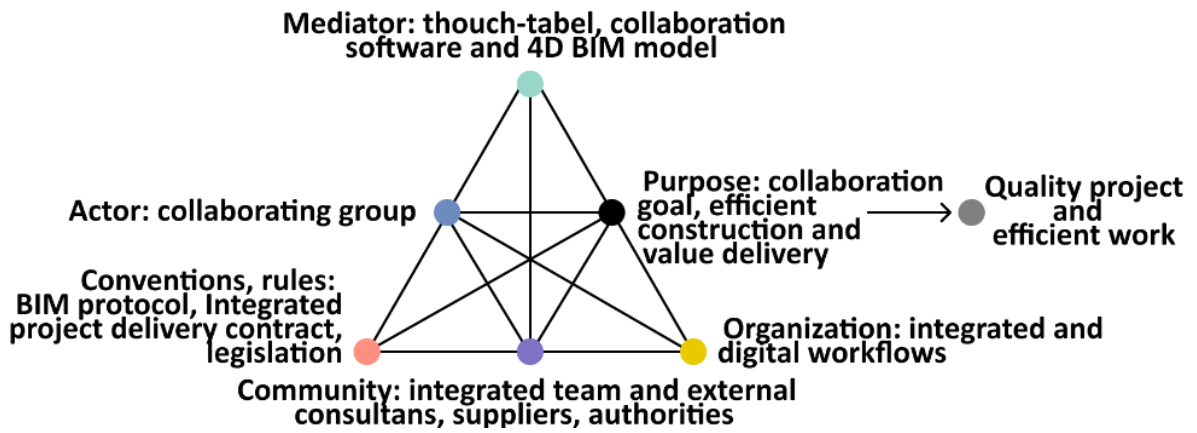


Figure 43 Schema of a collaborative decision-making by a construction project team with digital tools at the project meeting

Key points of 2.1.2

Approaches and theories for studying collaboration with digital tools

- The STS thinking approach allows to describe organizational systems and to study collaborative interactions with mediating digital tools. STS allows description of the systems encompassing technology and social aspects of coordination, collaboration, and culture. Theory allows us to describe a macro level of BIM-based collaboration. Fostering sharing knowledge and collaboration is essential for a BIM/IPD project. An efficient STS would foster such sharing with the social actions. The mediating artifacts may be represented by not only physical objects but also abstract phenomenon.
- The use of computers and digital tools became essential for many domains, work practices and personal tasks of humans. Following the emergence of personal computers and rapid development of digital tools, various fields, and approaches to studying their interactions with humans have emerged. Thus, the field of HCI proposes the solutions to answer the need for 'people-oriented computers'. Moreover, the implementation of UCD based on an early focus on users and tasks, empirical measurement, and iterative cycles design, allows to develop the new digital tools which accumulate the best qualities of effectiveness, usability and usefulness.
- STS theory and design became a part of a variety of studies concerning different domains, including AEC industry and BIM domain. BIM adoption requires an integrated approach combining technical structures and social practices. Socio-technical system approach, various scholars have implemented AT approach and UCD approach to investigate different aspects of BIM use and collaboration.
- Our research approach combines the concepts from Socio-technical systems, Activity theories and User-centered design, and provides us with the theoretical frame for further investigation and prototype evaluation. Socio-technical system provides a description of the complex context of use of BIM and other digital tools as mediators for collaborative work on a project. Activity theory further presents us with the instruments to describe a model of collaboration activities, to encompass actors, collaboration, tools, rules, teams and the context into to the model. User-centered design provides the methods of fostering usability, effectiveness, efficiency and usability aspects of the development of collaboration tools and scenarios. Such combination provides the conceptual frame to determine and evaluate our proposals.

2.2 Collaboration tools: a need for digital continuity and interactivity

2.1

2.2

2.2.1 Overview of BIM and Lean collaboration solutions

2.2.1.1 BIM tools and collaboration studies

Link between distant and co-located BIM-based collaboration tools

BIM collaboration practices rely on both distant and co-located digital solutions, mediating dataflow, design and value engineering. They are connected and aim for digital continuity of the data.

The amount of data and its complexity increases through the project life cycle. They grow around the 3D in a center of collaboration and exchanges. The 3D BIM model gathers information about the model's elements properties and connects them to the other project documents. Project development and decision-making strongly rely on a management system of project information documents and on information representation interfaces (Kvan, 1999). A variety of digital solutions is available to AEC professionals for collaboration, mediation of distant or co-located design, analysis, and decision-making.

BIM tools enable parametric modeling and allow new levels of spatial visualization, simulation of the behavior of the building, as well as more efficient project management. (Miettinen and Paavola, 2014). Regarding software purposes it is possible to distinguish the BIM tools classes as:

- *services,*
- *catalogues,*
- *servers,*
- *viewers,*
- *modelers,*
- *mobile,*
- *checkers,*
- *management,*
- *simulation,*
- *communication,*
- *publishing,*
- *query, and utilities (Wallner and Von Both, 2017).*

The “4D” and “integrative application” software types enabling interactions with 4D information (Porkka and Kähkönen, 2007) correspond to the ***viewer-modeler-checker classes***.

A study of BIM-based synchronous collaboration for project design purposes proposes to use the ***Model–View–Controller (MVC)*** framework (Figure 44). It also proposes new patterns which support design of user interactions with collaborative tools. In the framework, Model is the BIM model and its domain a specific view which is updated in real time during synchronous collaboration (Isikdag and Underwood, 2010). This study of collaboration for project design purposes highlights that ***collaboration efficiency is strongly dependent on coordination and communication*** (Isikdag and Underwood, 2010), which are the prior collaboration levels of the collaboration continuum. The focus of this study is mostly on design activity, yet it highlights the same barriers which are relevant to collaborative decision-making

mediated by BIM. It emphasizes the importance of user interactions for higher efficiency of collaboration.

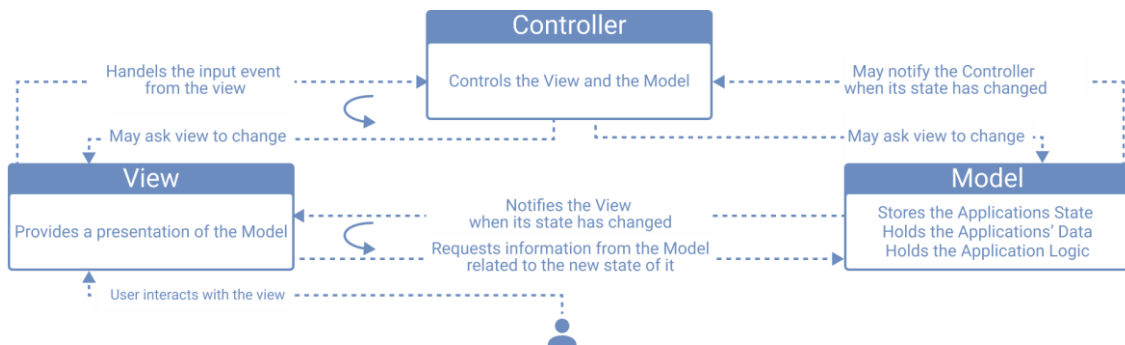


Figure 44 Generic structure of Model View Controller framework adapted from (Isikdag and Underwood, 2010)

Naturally, AEC project collaboration with BIM in the digital core of the work processes would first rely on digital tools like servers, platforms or more complex technological systems. Distant collaboration solutions, such as document management systems like *virtual clouds or intranets*, allow the design and construction team to automate uploads, sharing and approval of project documents (Singh et al., 2011).

Many cloud-based IT solutions offer various *collaborative modeling* features (Boton, 2018). The cloud-based solutions are not always a part of a usual practice. However, they must allow an option of a customized design document management. Construction project case studies illustrate that cloud-based synchronization and design information exchanges are possible, and yet they *lack improved collaboration features* and BIM workflow tools (Munkley et al., 2014). According to Munkley et al. the cloud platforms and services still lack a wider range of functionalities *specifically useful for BIM projects*. Moreover, BIM users face intra-organizational challenges, for example the project document exchanges must be adapted to the *internal and external workflows*, and to *correspond to the management standards* (Vass and Gustavsson, 2017).

The ideas of connecting project data are related to the development towards interoperability, which today takes into consideration not only technological, but also social, procedural, legal and strategic aspects of collaborations. Miettinen and Paavola predicted the future development of BIM implementation fostering the shift from a fragmented to an *integrative way of construction*. They observe that most BIM implementation studies take a *socio-technical perspective*, and suggest that while BIM fosters changes for the technological core, it also impacts the social aspects, therefore *IPD and Lean construction become frameworks that adapt the social aspects such as collaboration and organization*, as well as adjusts the legal frame (Miettinen and Paavola, 2014).

However, Miettinen and Paavola outlined as well that within a specific circumstance a fully integrated and co-located team would not yet be the most efficient, therefore *"... efficient tools and collaborative ways of solving critical tasks in the design, construction, and FM process will be developed."* (Miettinen and Paavola, 2014). Potentially, an intermediate solution between traditional and fully integrated approaches would be useful and would foster the full integration. Thus, less complex, and integrated systems may become an instrument for such transition and provide easier implementation.

Paper, digital and BIM-based synchronous collaboration studies

Even before the emergence of BIM, one of the visionary early studies by Collier and Fischer stated the ideas about shared distributed use of 3D/4D models. Their research outlines that presentation of a *physical model is not the same as of a virtual model*, and considers possible *use of an “electronic table” for collective project review with a 4D model* in the future (Collier and Fischer, 1995). Following the same line of research, a proposal of interactive 4D-CAD as a “... ‘decision’ tool which supports both the process of building the schedule as well as the evaluation of its viability.” (McKinney et al., 1996). The study also describes 4D library, 4D model and 4D interface, as the components of the proposed system of 4D-CAD, which emphasizes the place of the stored project data, 4D connection creation and the importance of the user interface.

Likewise, before the establishment of BIM, research investigating more cohesive interdisciplinary “*extreme/radical collaboration*” by Chachere, Levitt and Kunz describes the organization which relied on a shared digital model to structure their co-located collaboration (mostly regarding design tasks, but also decision-making sessions) with a contract, training and culture, with progress visualization on large interactive graphic displays. The study outlines *the tightening collaboration as a strategically powerful tool* for most projects (Chachere et al., 2003). Further, after the analysis of observations and models Chachere, Levitt and Kunz highlighted that in order to achieve enhanced collaboration there is a need for *minimization of coordination barriers: physical, social and technological* (Chachere et al., 2003). This would require the adjustment of collaboration setting, processes, and tools.

Following this line of studies, who propose a *DEEPAND framework* allowing to analyze the effectiveness of multi-stakeholder meetings with the description structured by classification of per locutory statements (communication activities) in meetings, which include: *describe, explain, evaluate, predict, alternative formulation, negotiate, and decide* (Garcia et al., 2003). The activities of description and explanation assist with identification of relevant and accurate information, and take most of the meeting time, which is necessary, but could be considered as “waste,” since the other activities are thus more focused on value engineering and decision-making. Therefore, more integrated and decision-making focused tools must be provided to foster collaboration efficiency.

Many research works have been dedicated to developing Computer-Supported Collaborative Work (CSCW) scenarios and environments for AEC and design, therefore various collaborative solutions experiments were performed to reveal a potential usage of various *types of mediators, such as 3D virtual workspace environment, holodesk with direct 3D interactions on a see-through display, of life-size 2D sketch representations and hybrid ideation space with an even more immersive environment* (Achten, 2001; Achten, 2002; Dorta et al., 2011; Hilliges et al., 2012). These studies illustrate the relevance of the mediating digital tools topic, and research for the most efficient visualization and interaction tools.

A series of papers presents the research studying first the physical artefacts (paper-base) and digital artifact-mediated collaborative activities, and next the BIM-based collaborative activities and practices, visualization and mediation tools. Tory and Staub-French propose a quantitative analysis of visualization which issued from use-cases studies of collective use of visual representations. In addition, the analysis follows the grounded theory approach, and it argues that further development and implementation of *qualitative studies by researchers would only bring benefits to understanding of visualization and coordination*, and complement the quantitative analysis (Tory and Staub-French, 2008). Thus, the further implementation of qualitative and quantitative methods would provide benefits to the body of knowledge on collaboration.

Additionally, the study observes certain *ineffectiveness of use of project documents during the meetings*. It reports from the meeting observations that *descriptive and explanative tasks* were the most recurrent, unlike *predictive and evaluative tasks* recurring in a little more than 10% each of meeting time. Moreover, observations report *that the use of digital supports directly influenced meeting interactions* with project documents disregarding the project documents contents, reporting that “... *pointing and gesturing accounted for 84% of interactions in paper-based meetings and 47% in digital meetings*”, and that “... *manipulating and accessing accounted for 8% of interactions in paper-based meetings and 29% in digital meetings*” (Tory and Staub-French, 2008). These observations follow the ideas presented by *in studies of iRoom* (Liston et al., 2001) highlighting the need to enhance the users with tools supporting predictive tasks.

Also, the study proposes to *use categories for the outline of meeting process*, and to create a basis for the future, more precise development of requirements for user interactions with technology and with each other through description of:

- *subjects (meeting participants),*
- *scene,*
- *tasks,*
- *artifact,*
- *artifact type,*
- *artifact form,*
- *bottlenecks (Tory and Staub-French, 2008).*

In this study the artifacts “...*represent the building design information,*” and they “... *include digital and physical 2D schematic diagrams and 3D models*”. Thus, the term encompasses both paper and digital project documents, and interaction is “... *cognitive or physical engagement with artifacts, in other words, the active use of artifacts*” (Tory et al., 2008). The meetings may focus on design development or on value engineering. The proposed categories present a frame to describe the meeting purpose, participants and used documents, however it does not include user interactions with technology into to the description scope, nor nD BIM documents.

The study by Tory and Staub-French also reports that the used project documents (visual representations) and their limited interactivity influenced meeting bottlenecks (Tory and Staub-French, 2008), thus there is a potential *value in improvement and optimization of interactive decision-making supports* to enhance meeting efficiency. Consequently, they suggest a CSCW technology would mediate project meetings (Tory et al., 2008), and from the software point of view, the study outlines a *need to enhance usability of digital project documents* with a *specialized and customizable* application for collaborative decision-making (Tory and Staub-French, 2008).

In addition, in the same line of studies Dossick and Neff have investigated communication and collaboration with BIM, which occurred not only at interorganizational level, but also at the level of collaborating individuals (AEC professionals), by observing the weekly project meetings. The authors report on “... *a paradox in how BIM supports collaborative work: BIM excels at helping people find problems, but does not support the dialogue needed to solve many problems encountered in complex design and construction projects.*” (Dossick and Neff, 2011). Moreover, they conclude that the *collaboration is inherently messy*, thus Dossick and Neff proposed to distinguish “clear technology” (data exchange) from “messy talk” (human interactions), where BIM supports “*the exchange of explicit knowledge*”, and the messy talk is defined as “... *the interstitial dialogue between and after formally organized agenda items.*”, and essentially represents the topics not outlined in a meeting agenda, and even may be informal, active and flexible (Dossick and Neff, 2011). Such approach emphasizes the

importance of a balance between social and technical aspects of BIM collaboration, yet it does not study the actors' interactions or the more extensive use of BIM.

Conrad Boton studied BIM and 4D based collaboration, and proposed visualizations specifically adapted to each project discipline needs at the collaboration session with collective use of 4D (Boton, 2013). Thus, the study outlines the requirements for visual representations of project information, the project views *adapted to specific need of AEC disciplines*: 2D representations, 3D monochrome, 3D textured, Gantt chart, PERT, linear planning (Boton, 2013).

In addition, Boton emphasizes task (aims) types of 4D simulation visualization:

- *data visualization,*
- *positions localization,*
- *dependencies identification,*
- *tendencies deduction (Boton, 2013).*

Such emphasis allows to consider various adaptations of the user-interface during collaboration tools design and emphasizes the need for different representation of information relevant to the tasks, users and planning decision-making scope.

Poirier et al. approach collaboration studies on an inter-personal level, however such collaboration is still similar and connected to interorganizational collaboration level (Poirier et al., 2016). The study suggests that a *collaboration system includes structure, process, artefacts, and agents*, and is *influenced by the context* that forms it and *the events* it causes. Poirier et al. implement the following framework for collaboration description and analysis:

- *who is being investigated (i.e., which agent in the project team or the supply chain and the relationships that structure the project team);*
- *what is the environment (i.e., the context);*
- *what tasks are investigated (i.e., the processes underway);*
- *how is it being investigated and measured (i.e. the mechanisms deployed in the forms of project artefacts and the outcomes of the building project) (Poirier et al., 2016).*

These elements of framework offer us tools to portray collaboration.

Further, following the same line of studies as Tory and Staub-French, and investigating paper and digital mediators use at the meetings, Mehrbod et al. report that *interactive displays enhanced interactions and sketches*, despite all mediators being used almost equally, the 3D was most used to prepare and navigate the design information, however, to record their decisions the observed project team members preferred to use paper (Mehrbod et al., 2019). Thus, there is a great potential in use of digital and analogue project documents as decision-supports, however, there is a *lack of efficient digital tools to record meeting decisions*.

The study reports on frequency of goals (see Mehrbod et al., 2019)., influencing transitions between different design artifacts and views with *obtaining better view, model query an directing attention being the most common*. It reports as well that *document navigation is an activity occupying more than 60% of the meeting time and that 2D drawings, 2D PDFs and 3D Models (Navisworks) were the most used types of mediating artefacts* (Mehrbod et al., 2019). This suggest the importance of efficient and accessible for all project team members interactions with the project documents and provides the requirement for efficient navigation interaction. It also suggests that despite the use of BIM for project design and for value engineering, the analogue and digital tools must still be considered as mediators at the meetings.

In addition, the study also suggests that in future collaboration settings a use of *cloud BIM platforms* could improve access to project information, and even *foster BIM implementation* into practitioners work processes. However, to assure the usability of BIM there is a *need to adapt navigation interactions* for better interactivity and project meetings, as well as to *implement interactive displays* (Mehrbod et al., 2019). Table 8 summarizes the presented studies approach, methods and findings.

Table 9 Summary of Paper, digital and BIM-based synchronous collaboration studies

| Study | Approach | Methods | Collaboration | | | | Supports | Technology and HCI | Findings |
|-----------------------|--|---|---------------|----------|------------------|------------|------------------------|---|--|
| | | | Scope | Location | Design Decisions | Co-located | | | |
| Chachere et al., 2003 | Extreme/radical collaboration | Session's observations | ● | ● | - | ● | Pre BIM | large interactive graphic displays | Identified a need for minimization of coordination barriers: physical, social, and technological |
| Garcia et al., 2003 | DEEPAND framework | Speech acts theory, Ethnographic observations | - | ● | - | ● | Pre BIM | - | Classification of communication activities: Describe, Explain, Evaluate, Predict, Alternative formulation, Negotiate, and Decide Meeting effectiveness evaluation |
| Tory et al., - 2008 | - | Grounded theory, Session observations, Case study | ● | ● | - | ● | Paper, digital | Interactive displays Interactions analysis | Ineffectiveness of use of project documents during meetings: predictive and evaluative tasks recurring in a little more than ten percent of meeting time, Users interacted more with digital supports, Categories to outline meeting process |
| Dossick, Neff, 2011 | Clean technology and Messy talk distinction | Grounded theory, Empirical field research, Ethnographic observations, Interviews | - | ● | - | ● | BIM, paper | Digital projections and annotations | Messy talk: interstitial dialogue between and after formally organized agenda items, Paradox of BIM support of collaborative work, Dimensions of communication: formality–informality, passivity–activity inflexibility–flexibility |
| Boton, 2013 | Discipline specific 4D views | UCD, IDM Design science Analysis, Observations, Case study | - | ● | - | ● | BIM 4D | Interface and inter user interactions | Empasis information types, visualization task types, 4D views adapted to AEC disciplines |
| Poirier et al., 2016 | Framework for collaboration description and analysis | Critical realism Analysis | ● | ● | - | ● | BIM | Inter user interactions | Collaboration system: structure, process, artefacts, and agents Collaboration system is influenced by the context |
| Mehrbod et al., 2019 | Interaction taxonomy | Ethnographic study, taxonomy to represent the relationships, Session observations, Case study | ● | ● | - | ● | Paper, digital, 3D BIM | Interactive displays Interactions analysis | Interactions: preparation, annotation, navigation, recording. Analysis of design artifacts use a lack of efficient digital tools to record meeting decisions |

2.2.1.2 Development of 4D-based collaboration solutions

Development of solutions for 4D simulations and interactive workspaces use

Digital tools are essential for a variety of work practices. Software vendors and academic community both proposed, developed and improved many digital solutions (software and hardware) for AEC professionals. The following section provides an overview of these digital solutions to emphasize the development scope and variety of options. Each solution development was naturally influenced and guided by specific requirements and specific usage. Such development experience must be considered to gather the optimal set of user requirements and to benefit from the experience of the previous solution development efforts. Since the digital tools development is very prompt, the overview is limited to a selected number of solutions.

The study conducted in CIFE^{xi} experimenting with *iRoom as the technology-rich interactive workspace* by Liston et al. investigates collaborative decision-making by a multidisciplinary team with *digital and analogue supports (mediators)*, and points out that paper-based project information as a support is limited, since it *does not highlight the most relevant information* and does not enhance the project team's *focus on the problem to foster decision-making* (Liston et al., 2001). To overcome such limitations, the digital mediators' interface and interactions design must account for the need for relevant information visualization.

The experimentation and analysis of the use of digital collaboration environment "iRoom" including high-resolution wall-mounted and tabletop displays, laptops and software, reports on positive effects of focused attention of collaboration participants to *relevant project information enhanced through interactive information access* (implementation of touchscreens), and relevant to the decision-making information, data sharing and visualization techniques (e.g., highlighting).

The collaboration observations outline the types of meeting tasks as *descriptive, explanative, evaluative, and predictive*. With the paper mediators they are descriptive and evaluative, yet with the 4D use they are mostly explanative (Liston et al., 2001). The study outlines that the use of interactive mediators would increase a number of predictive tasks and reduce the number of descriptive activities at project meetings. For instance with 4D visualization, the explanative tasks were more present than descriptive, and the use of the touch-screens allowed project teams to navigate information more efficiently, to shift attention from less relevant project documents and to improve team's focus on the 4D visualization, which also provides a large-scale view thus is more appropriate for group work. (Liston et al., 2001)

Even before the establishment of BIM practices, the study highlights the need to adapt digital information exchanges and work approaches, to manage project team effectiveness, as well as the need to share different kinds of information including cost, schedule, contract, etc. In addition, with the project model in the center of collaboration there is a *need for interactive multi-user interfaces* and for the relevant to a *group use view of the project* (Liston et al., 2001). Even though these limitations were outlined two decades ago, they are still remarkably relevant, and foresaw the potential in the use of interactive and intuitive workspaces, as well as of BIM nD models for collective decision-making.

This research on the subject of *interactive workspace* set a course for the emerging research topics of 4D use, HCI and BIM collaboration, by outlining that not only the technology and data sharing

^{xi} Center for Integrated Facility Engineering <https://cife.stanford.edu/>

problems, but also the issues related to visualization and user-interactions with the project information are essential for digitally developed AEC projects (Fischer et al., 2002).

Further, the ICon Lab study by Maldovan and Messner investigate the potential of 4D model use for the construction schedule review enabled by an immersive display system (Figure 46) (Maldovan and Messner, 2006b). The study investigates the potential value in use of such immersive virtual environments as a decision-making environment; and it reports the positive results from the improved communication, and from the project team feedback on *usefulness of 4D schedule review for validation and optimization, achieved through more time predictive and evaluative conversation* types, with less on discussions than a traditional project meeting (Maldovan and Messner, 2006a). Therefore, the value of 4D use investigations confirm benefits and outline the use requirements. The optimal visualization and collective interactions with 4D were investigated as well, emphasizing the importance of large-scale representations. Hence, by the time of BIM diffusion, already various 3D enabling and 4D enabling tools were explored as mediation support for the project and construction management.



Figure 45 iRoom: Interactive Workspace (source (Liston et al., 2001)



Figure 46 Review meeting in ICon Lab (source (Maldovan and Messner, 2006b)

Following research on 4D modeling tools creation and validation by AEC professionals, Dawood et al. present *VIRTUAL CONSTRUCTION – VIRCON* system as a new 4D-based planning tool and decision support allowing the tasks sequencing review with their connection to the model elements of the construction site. In addition to the distant planning, the system enabled better understanding of the project (Dawood et al., 2005). The study emphasized the *need for interoperability with scheduling software*, representation of all kinds of construction and supporting activities, need for an easy and user-friendly access to the model hierarchy and for the interface filters.

With the development of 4D views, the clarity of visualization became an essential, yet complex issue. Hartmann and Vossebeld *analyze efficiency and highlight signs* of construction process visualizations, which represented the contextual information. They report on a project with a large number of risks, which presented challenges to the visualization clarity, thus the team developed a system with the signs to represent risk-specific contextual information, and with the specific colors and 3D letter-signs which represented a functional meaning (Hartmann and Vossebeld, 2013). The system allowed risk identification and mitigation at the meeting, enhanced understanding of safety and health risks and make their location more explicit (Figure 47). The study emphasizes that the need to highlight an object of the model is different from a need to highlight a risk-related area. Moreover, to enhance visualization and understanding by various team members there is a need to use icons as well (Hartmann and Vossebeld, 2013). In addition, the study identified the need to create visualization conventions.

Davies and Harty experimented with *“Site BIM” platform* to support construction of a use-case at the construction site (large hospital project) where the workers accessed design information, captured quality and progress with tablets. They report that the *use of the tablets was central in shaping information systems and processes* for the project, yet they mention some *difficulties regarding the use of touch screens with gloved hands and bulky cuffs* (Davies and Harty, 2013). 3D BIM model viewer and document links associated with objects in the model allowed construction teams to avoid errors, and to capture site data, thus to ensure a better compliance with the design (Figure 48) (Davies and Harty, 2013). Thus, the use case presented the implementation of the tools for BIM-based coordination on site, and the importance of digital data continuity and efficient interactions with it.

In search for more efficient and automated 4D, a study by Kassem et al. investigates the existing solutions for 4D modeling, and outlines that most of the construction workspace management is issued with the help of design applications which limits the access to such management for the project planners. Also, the study outlines the low interactivity of the management solutions and their lack of IFC-compliant interoperability. Thus, the study proposes a 4D BIM tool enabling automation of workspace allocation avoiding spatial conflict, proposing conflicts resolutions and improving planning efficiency (Kassem et al., 2015). The solution proposed a 3D model with Gantt chart simulation visualization and proposed a highlight of the workspaces. Despite the number of limitations, the evaluations of the tool highlighted the potential of such approach and need for further development of more elaborate and user-friendly features assisting with automated and integrated workspace generation.

Elghaish and Abrishami developed *a framework to implement 4D solution aligned with IPD and* to create 4D links, since they identify a gap in most of the research focused on 4D BIM use but not as much was explored about 4D BIM features and processes (Elghaish and Abrishami, 2020). Thus, they *propose a new method to create the list of activities (processes), propose an integration way for Generic algorithm into BIM platforms using API, articulate a new approach to understand/utilize the output of 4D BIM*” (Elghaish and Abrishami, 2020). The “proof of concept” prototype of a *4D planner generic*

algorithm for automated 4D and planning production supported by BIM activity library and Navisworks environment, the approach also seeks to optimize construction methods simulations of each construction activity, as well as to link the proposed processes into a single platform (Elghaish and Abrishami, 2020). They also identify the future development potential in providing a link between 4D and 5D, and to build an integrated cost management system, and integrating them with the IPD analysis tools which allow to survey of shared risks and rewards (Elghaish and Abrishami, 2020). The proposed approach has a strong idea of solution the problem of optimization of planning and activities generation, as well as the idea of a “single platform,” yet not all the 4D BIM uses are integrated into the system, nor the interface is adapted to collective planning.

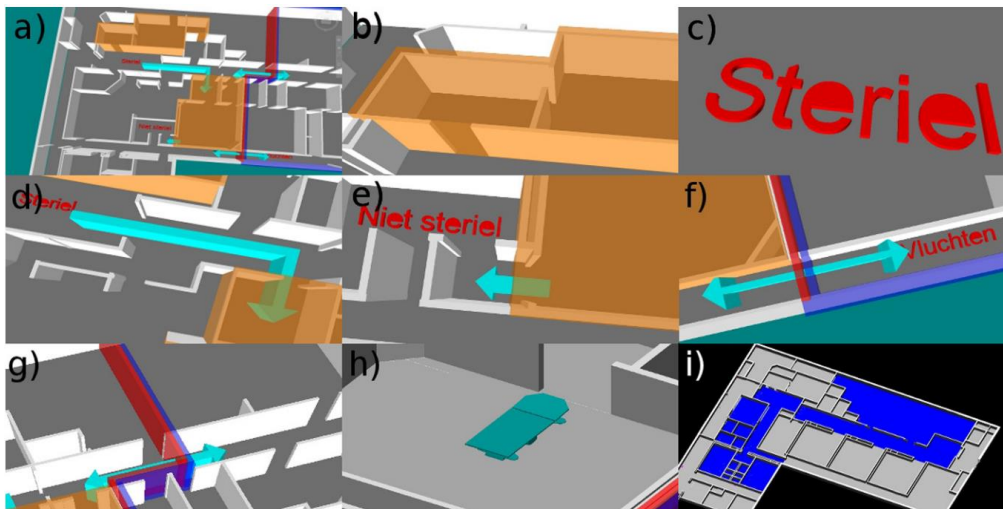


Figure 47 Illustration of the signs to represent risks (safety related) on a construction model (source From left to right, top to bottom: a snapshot showing an overview of how routing was visualized by different signs in combination (a), the use of semi-transparent orange fill to represent vulnerable rooms (b), the use of textual information (c), the use of a combination of textual information and a 3D arrow to represent specific routing related to the operating room, such as an ingoing sterile route (d), an outgoing non-sterile route (e), and escape routing (f), the use of red walls to indicate dust barriers (g), the use of an operating bed object as reference-point within the model (h), and the use of floor surface colors to indicate air-pressure zones (i)

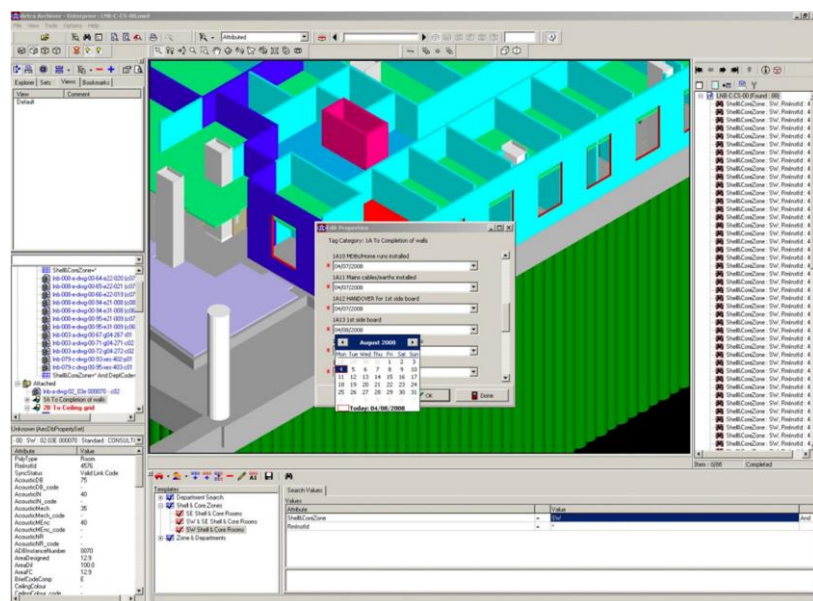


Figure 48 Site BIM system: Site dBase to enter progress data for consulting room (adapted from (Davies and Harty, 2013)

Immersive solutions for 4D use

A variety of solutions and studies proposed 4D use mediated with mobile devices, Augmented and virtual reality, as well as with other immersive tools. For example, collaborative solutions, such as collaborative VR-based 4D simulation environment (Boton, 2018), or iRoom (Fischer et al., 2002), and VCE (Waly and Thabet, 2003), provide interactive and collaborative 4D solutions. There are also tools for construction monitoring with AR tools SiMaApp (Ratajczak et al., 2019).

Furthermore, to preserve data continuity, there are web-based BIM viewers such as Tridify BIM Publishing Service⁹ which proposes to upload multiple BIM models of a project on a server to share it with the project team. The web-based project BIM model review is possible not only for ***desktops, but also adapted for mobile devices and VR sets***, which offers a wider range of visualization possibilities for the users. In the future, the possibility to switch from a desktop to VR or AR would be a way to improve visualization quality.

In addition to visualization, the project team may comment on the model and the service generates a BCF file, which could be integrated into the workflow. Thus, such tools enable annotations and cooperation, and allow to enhance immersion with the models.

McCoy et al. describe a methodology for image-based reconstruction techniques for remote site construction planning, and in particular the use of ***D⁴AR approach for Four-Dimensional Augmented Reality Modeling*** (McCoy et al., 2014). The approach allowed to visualize a comparison between as-planned and as-built with the daily follow-ups' photographs and 4D models with mediation through mobile phones. The approach relies on the use of mobile devices and AR on site, and thus outlines the importance of usability of the tools enabling 4D BIM use on site, and the need for digital continuity of the BIM data.

Jallow et al. present feedback on a case study implementing ***BIM and 4D for an infrastructure project*** development, where a use of 4D sequence was initially requested by the project client. 4D mediated collective decision making and enabled the adjustments of project design to the program requirements, as well as it improved with a VR walkthrough the understanding of construction planning with by the construction teams and by the client (Jallow et al., 2019). Such implementation illustrates the potential of immersion and efficiency of the 4D visualization.

One of the examples of digital tools development from academia is the "ACCEPT"¹⁰ research project aimed to provide AEC professionals with digital technologies (system of 3 tools: ***dashboard, AR application and mobile application***) to improve quality assurance of a construction project on site (Ratajczak, Marcher, et al., 2017). The project did not put 4D or collaborative decision-making in the focus, yet there are some common investigation points with our research.

Another study also explores the use of VR as a mediator for 4D modelling and collaborative planning and compared it to the traditional CPM method (Tallgren et al., 2021). The reports a need for a user-friendly interface improving the complexity of the 4D modeling tools, which are complicated and require special training. Moreover, the 4D modeling tools have a limited use for collaborative planning. These limitations are proposed to be overcome with implementation of VR tools.

Ratajczak et al. describe a scheduling and monitoring with the help of a *SiMaApp* mobile application for visualization of location-based scheduling Gantt chart. However the application is developed with Lean Construction methods approach to schedule details to improve productivity and adapt the information to the application user (Ratajczak, Schimanski, et al., 2017). They propose to use "A Tiered Structure (TS) methodology" to allow users to access the relevant required information, and to establish

the breakdown structure of a project, responsibilities, and controls. In the proposed application the information levels are:

- **building and construction phase** *owned by client and general contractor,*
- **construction work packages** *owned by project manager, architect, and engineer,*
- **construction tasks** *owned by site manager,*
- **construction activities** *owned by supervisor and workers.*

This application highlights *the need to adapt the information to the project development phase* and to the AEC professionals' (users') needs for information visualization and proposes to do so through lean construction methods.

The other part of the project developed a *Dashboard* tool, a web-platform for the use on desktops, including sensorial data into project information for control and offered the construction quality control through questionnaires (Ratajczak, Marcher, et al., 2017). This prototype highlights the *need to access the "united" data on the project, the need for a "control board"* (Martínez et al., 2015) as well as fosters the use of an early implementation of IoT elements for construction monitoring. The Dashboard tests by architects and site managers provided feedback on users appreciation of BIM and linked schedule progress visualization, an improvement of construction efficiency metrics (Ratajczak et al., 2019).

Commercial solutions for 4D BIM and planning

Commercial software and application solutions (tools) *evolve rapidly and update their features,* structure and even a development company, therefore a detailed review of 4D BIM applications would be promptly obsolete. Even from the beginning of this thesis study these various solutions have drastically changed. However, an outline of some applications which are today the most well-known by AEC professionals and implemented into the practices is essential for a portrayal of the current context, users' options and requirements for the new tools.

The planning and scheduling activities for AEC projects may be supported by various digital solutions. Like, *MS Excel*, which is mostly used for simple planning work, with relative ease of use and understanding. *Microsoft Project* is one of the most often used tools, enabling Gantt planning and CPM¹¹, with an access to synchronization with calendar, reporting, resources and costs. *Primavera P6*¹² adapted for AEC planning, CPM outline and progress tracking large and complex projects with a high number of tasks. These tools enable planning and scheduling, yet their core functions are not focused on BIM workflow, neither they provide a 3D. However, the scheduling information issued and shared through their native file formats is often imported into the 4D BIM software such as Navisworks or Synchro, which illustrates their relevance to construction planning activities. Moreover, Lean construction adoption and practice also fostered development of Lean specific digital solutions, which focused on lean principles implementation for construction management, aside a few exceptions without connection to BIM workflows.

Before the emergence of the ideas about nD BIM, and needs for more integrated digital information, design tools and planning tools did not have an interface for joining "various dimensions" of information types use for modeling and simulations. The 4D BIM solutions development by the efforts from academia and industry reveal novel uses for 4D and novel users' needs guiding the tools evolution. 4D BIM tools provide the users with different instruments and enable *animations and simulations, planning and scheduling, scenario comparison, 4D clash detection, resource management, reports, monitoring and tracking, export and import options, cloud connection and collaboration.*

Various commercial software for 4D modeling and simulation, or planning are available to AEC professionals, such as: Navisworks¹³, Synchro¹⁴, VisiLean¹⁵, VicoOffice¹⁶, Navigator¹⁷. The following figures illustrate their interfaces (Figure 49, Figure 50, Figure 51, Figure 52, Figure 53). Other commercial software for simulation and planning are available as well, such as: Asta PowerProject BIM¹⁸, ALICE¹⁹, Fuzor²⁰, BIMXtra²¹, Revizto²², Procore²³, etc. There are also commercial platforms for construction management: BIM 360²⁴, Aconex²⁵, Sablono²⁶, BIManywhere²⁷, Fieldlens²⁸, etc.

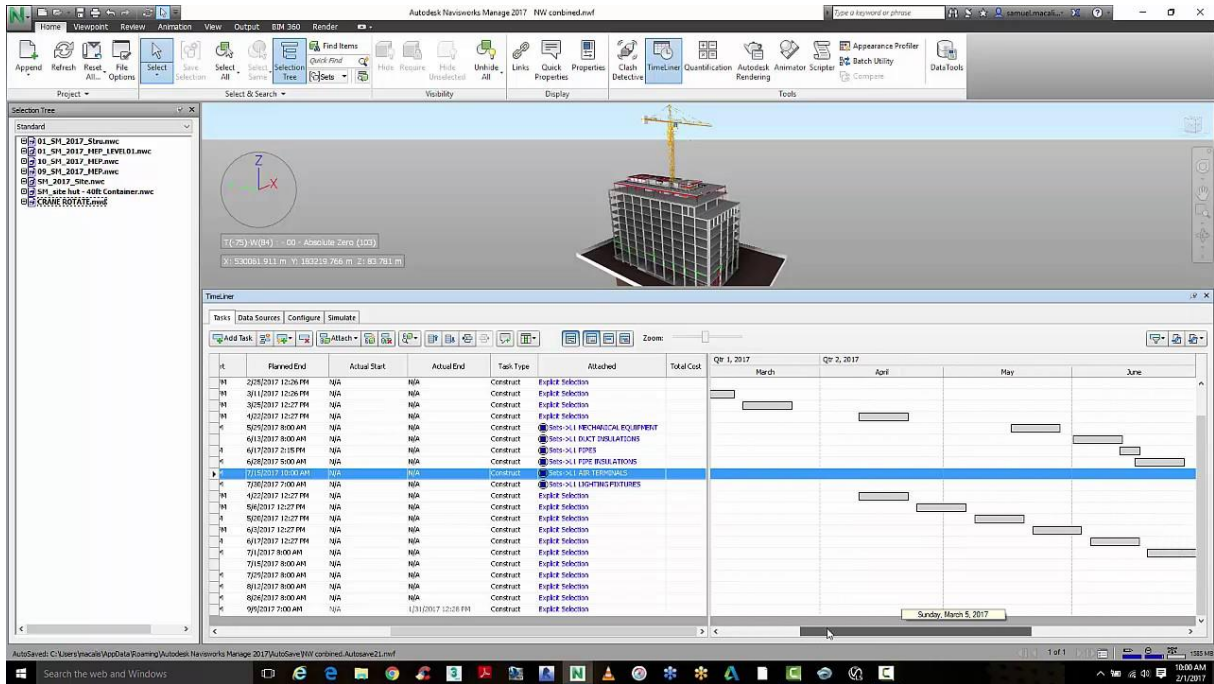


Figure 49 Autodesk Navisworks manage 2017 Interfaces: selection tree, 3D view, Timeliner (source Autodesk ANZ "Navisworks Manage timeliner overview"²⁹)

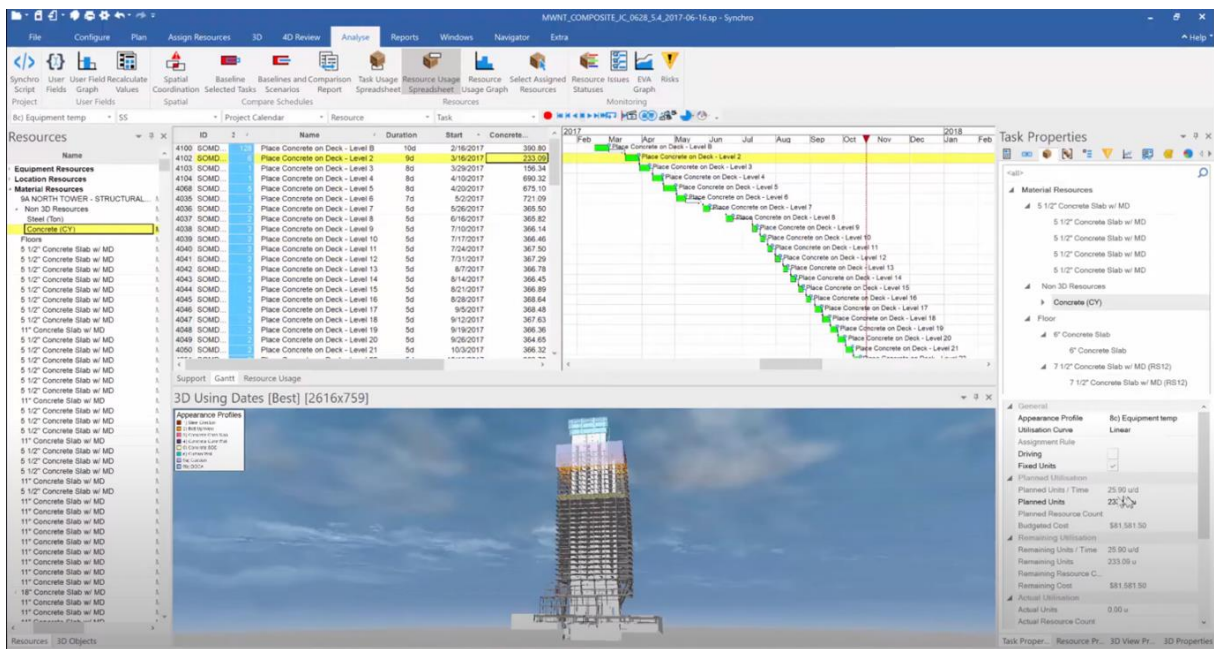


Figure 50 Synchro PRO interface: resources, Gantt, 3D view, task properties (source SYNCHRO Construction "SYNCHRO Pro 2017 – New Features"³⁰)

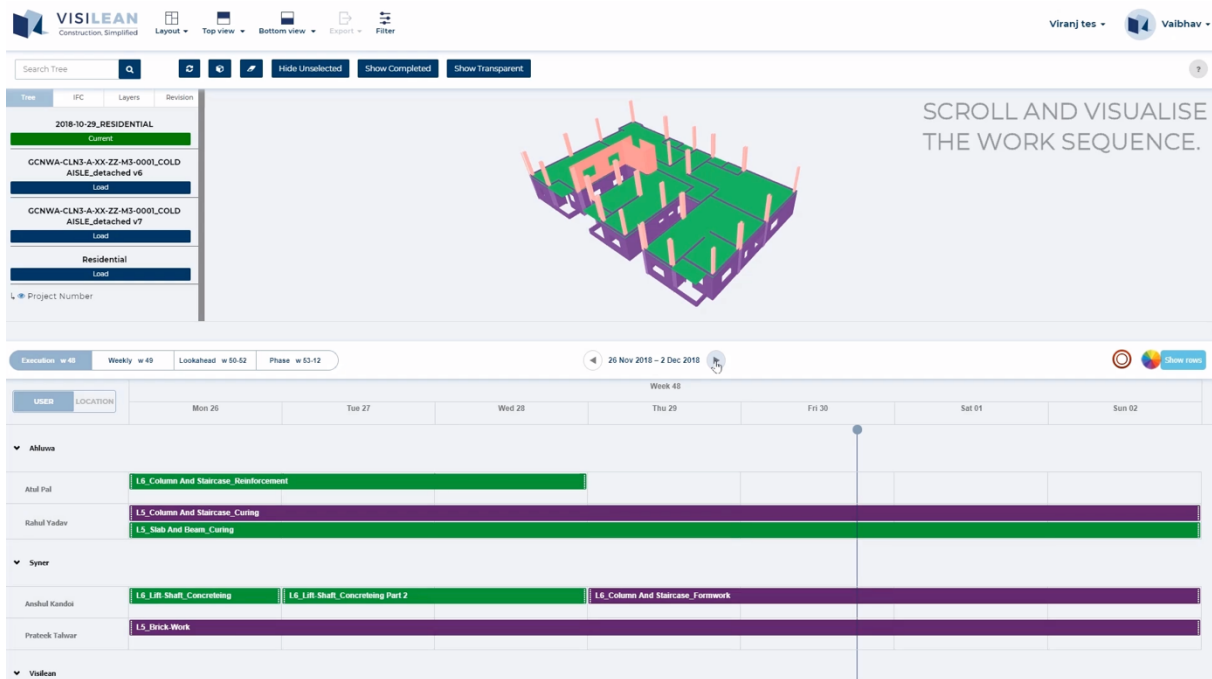


Figure 51 VisiLean interface: tree, 3D view, tasks view (source “Lean 4D with VisiLean”³¹)

Moreover, within the development tools supporting nD digital continuity, many solutions allow AEC professionals to encompass other dimensions than 4D; such as the solutions linking 4D to cost management as 5D solutions: *iTwo*³²(Figure 54), *Assemble systems*³³, *Cubicost suite*³⁴, *Innovaya suite*³⁵ (Vigneault et al., 2020). When choosing a 4D tool, it should be considered which functions are required, which may vary depending on the company and the project it will be used on. The particular aim of each software determines the available features, interface design and integration into BIM workflows, as well as it adapts to the target users.

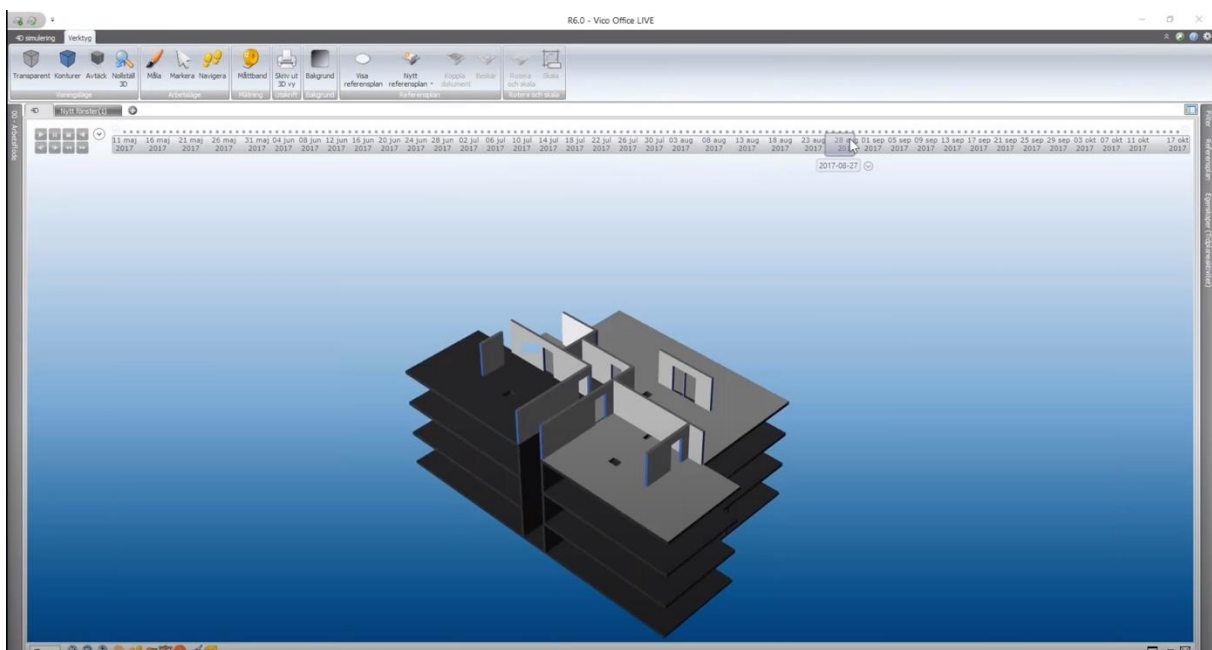


Figure 52 Vico Office – 4D simulation (source Vico Sweden “Vico Office – Steg för Steg”³⁶)

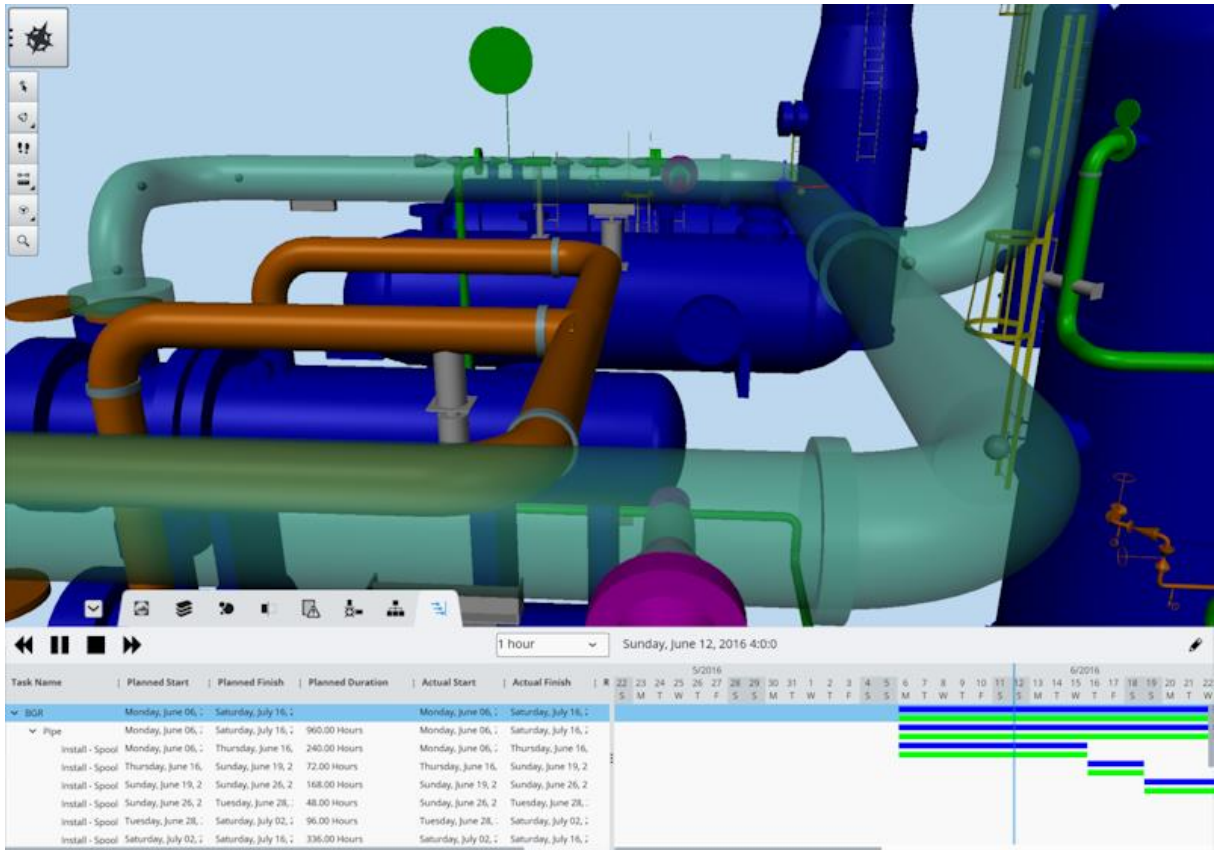


Figure 53 Bentley Navigator interface with 3D view and Schedule tasks (source Bentley Navigator product documentation³⁷)

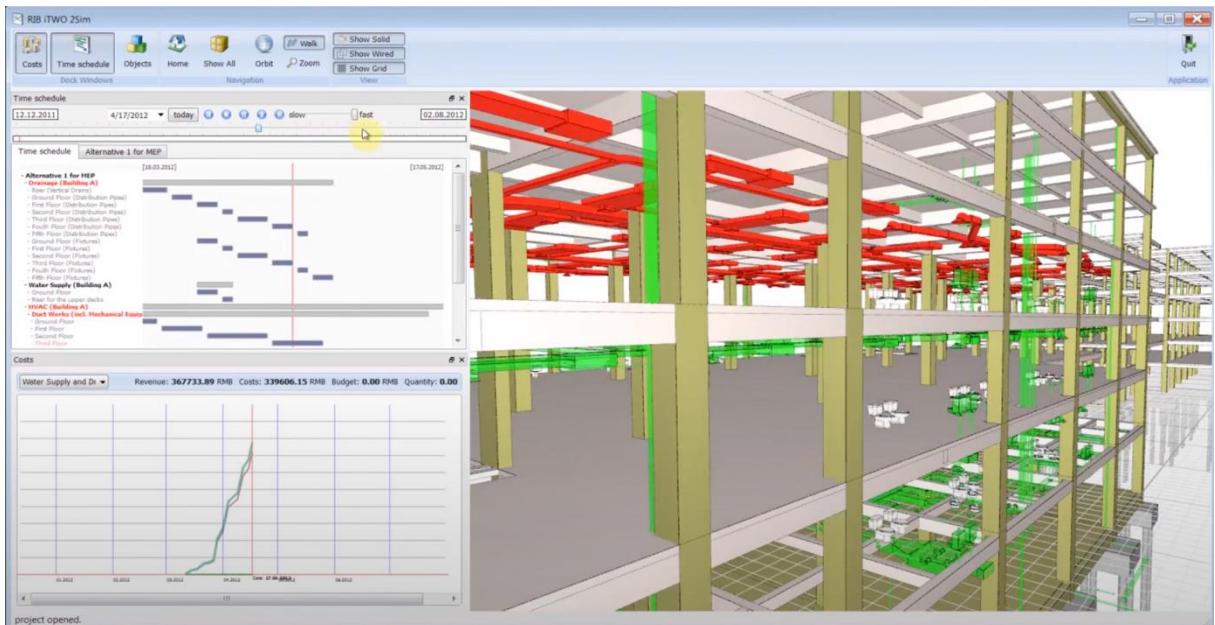


Figure 54 RIB iTWO interface: time schedule, costs, 3D view (source RIB Software "iTWO 5d simulation video" ³⁸)

Emphasis of the features of 4D BIM commercial solutions

Navisworks and Synchro are the most often cited commercial tools for 4D modeling and simulation. Navisworks by Autodesk, one of the commonly used 4D BIM tools, provides AEC professionals with a complex environment for 4D BIM use, enabling 4D modeling and schedule simulation. It is a tool for 4D

visualization of the project model and simulation. The visualization quality and ease of understanding is enhanced by filtering options, as well as by various 3D styles managing lightning and materials from a minimalistic a schematic representation to more detail focused realistic textured representation of the project model. The *4D simulation* settings also enable the global view or camera path simulation with an option of playback speed selection. With 4D visualization feature Navisworks may be used as a mediator for fostering better understanding of the project. However, the user interface is designed for *single user interaction on desktops*, thus the use of Navisworks as a support for collective interactions at the meetings would be rather limited and not enabling interactivity.

Navisworks also supports BIM interoperability, and it allows to *import Gantt charts* from a variety of sources. But it is rather adapted for closed BIM processes. The *clash detection* between different BIM models is one of the main uses of Navisworks allowing to avoid construction errors and coordination. Another core use is for *quantity take-offs* is enabled by the quantification function.

The schedule visualization with Navisworks is enabled by Gantt chart, which does *not offer a precision for a level of detail adapted for weekly planning* and management of construction activities and tasks. Moreover, the connection of Navisworks to construction activities administration on site stays limited as well, being rather adapted for decision-making on the management level. Yet, the access to presentation of the model can also be customized to the user, as one can select a selection of the objects from the 4D model to be displayed on a mobile device on construction site with additional tools BIM 360.

A case study by Malsane et al. reports on the use of Navisworks for 4D construction schedule simulation and progress tracking, where “... simulation helped in understanding the flow of construction work through a visual medium” (Malsane et al., 2015), however, to accomplish detailed and relevant 4D simulation, various efforts alliancing modeling and planning were necessary.

Another 4D BIM tool commonly used by AEC professionals is *Synchro* software, which also creates a complex environment for *4D BIM use for modeling and visualization*. The *interoperability options* enable exchanges of scheduling data from the planning tools, and 3D BIM data from the modeling tools. The 4D model encompasses the schedule visualization with *Gantt chart* and the 3D BIM model. The *scheduler function allows modifications* of the planning and may be considered timesaving. Also, it enables *computing of CPM and complex task dependence*. A useful feature for decision-making is the construction *scenarios comparison*. The schedule activities and temporary objects can be added directly to the 4D model to create more detailed plan and a realistic simulation.

Synchro’s scheduler is perceived as user friendly with color code for the various levels in plan hierarchy. Yet, the user interface is as well designed for a *single user interaction on desktops* and perceived by the users as quite advanced, as a support for collective interactions at the meetings would be rather limited and not enabling interactivity, despite the touch-interactions option.

Another Synchro’s function enables the 4D BIM use of *clash detection* identification and reports. Also, to support the construction management it comprises functions of *quantities outline, materials tracking and resource allocation, progress management*. The interface filters the schedule task types, work groups and contractors. Synchro also provides the Gantt chart schedule visualization, which does *not offer a precision for a level of detail adapted for weekly planning* and management of construction activities and tasks. Yet, Synchro Site enables the construction site connection, follow-ups and 4D model visualization on mobile devices.

A study of a use case of 4D BIM use for construction progress survey with Synchro Pro and reports that 4D planning improved collaboration with better visualization and thus understanding of the project, the delays, and of the construction site. They also report that Synchro allowed “... *present a dynamic, practical and compelling video*” (Ellouzi, 2017).

In summary, they both provide users with a set of functions enabling 3D model connection to the construction schedule, 4D simulation visualization, clash detection and pre-construction preparations. These tools propose Gantt chart visualization of the schedule. They do not propose a dashboard view. They also enable progress tracking, but both are rather oriented towards use for managerial decision-making, and do not present an interface enabling easy and interactive collective use.

A few applications allow BIM and Lean digitally based joint implementation. VisiLean application development was initiated by the academia research and emphasized in the thesis by Bhargav Dave, and it became a commercial solution developed in collaboration with industry experts. The thesis proposes a construction management system that unites **BIM and Lean construction**, and the VisiLean prototype (2.2.1.2) (Dave, 2013). The thesis compared existing commercial, and academia issued systems, and concluded that most 4D solutions offer basic features of visualization, clash detection, 4D planning, marking up (annotations) and sharing of the models. Yet, the comparison results also highlight the **lack of effective support of lean construction process by the information systems**, and that BIM advantages are not enough exploited during construction, in particular “... *4D BIM systems that provide a master plan level overview of the project*” (Dave, 2013), and do not provide necessary level of detail to support for construction activities management.

The thesis also reports **limited capabilities of BIM tools for detailed production planning**, scheduling, and control. The analysis reported that Vico and Synchro provide some capability to provide detailed production planning, yet they **do not provide features for “pull” planning** with detailed constraints analysis, and from the interface design perspective outlines the need for training and experience to use the tools efficiently. Thus, according to Dave the gap is only covered by **KanBIM and VisiLean solutions** which support BIM and Lean Construction workflows. He outlines that KanBIM focused on construction field activities, production management and control system, and that **VisiLean focused on collaborative planning workflow**, and developing a production planning and scheduling system to create the backend for construction management system. Both systems are complementary to each other (Dave, 2013). Today it is **a cloud-based project management service connecting BIM with Lean planning** and LPS principles, also designed for construction workflows control, progress and reporting. The project data interoperability is supported with the open BIM, as well as input and output data in table sheet formats.

Another useful function of VisiLean allows adaptation of the schedule details with the planning levels, which display both the commonly used Gantt chart with CPM option and the lean planning **a master plan, a phase plan with possibility to insert new main and sub-activities and a weekly schedule**. Different construction teams have continuous access to their work packages and can contribute to the planning by creating an outlook plan and weekly schedule for their respective subjects. However, a weekly schedule requires large amount of data, which brings a large number of activities to the scope and may hinder clarity of visualization and thus understanding. Also, since VisiLean enables LPS approach tools, it also has the function of a checklist of the requirements which must be arranged for a construction activity to begin.

The 4D visualization is **enhanced color coding, and these different levels of schedule detail**. 4D simulation from start to end is rather not embedded as the core function. In addition, a dashboard view displays up-to-date statistics of activities that are stopped, delayed or completed, as well as percentage

of completions of the tasks for the last four weeks, for visualization purposes the project information becomes converted into statistics and charts. Thus, the interface is designed as user-friendly and adaptable to different planning needs, enables distant collaboration, with the single user-oriented interactions.

The information about construction is mediated through an internal notification system that informs about problems or delayed activities and supported by the information from a mobile application used on site. This allows a continuous access to the project data and enables progress management in more mobile way. Moreover, visual and text data sharing function makes it possible to update the real activity status to the plan, as well as to export the project reports.

McHugh et al. present the feedback from the use of VisiLean for weekly project meetings for a large complex project, and report that collaborative planning improved and enhanced communication between trades as well as the workflows (McHugh et al., 2019). The study conclusions outline that *"... solution has delivered a project safer, quicker and to a higher quality, whilst creating a better working environment"*. They also highlight the need to automate tasks linking to the project model.

In summary, VisiLean is a powerful tool representing the new generation of web-based collaboration, data and processes integration-oriented applications, which is enabling 4D models visualization and lean planning. The application development is prompt with the new features appearing swiftly, and interactions and interface design adapting not only to the desktop uses but to touch-based mobile uses as well.

Another tool enabling 4D use is Vico Office. However, the main use is 5D construction planning and control, features beyond most 4D tools. Vico Office processes and stores model information when extracting element geometry and properties. By default, the data publishing of Vico Office divides the data into categories: substructure, superstructure, exterior, interior and MEP. With an interface containing: document controller, constructability, takeoff manager, cost planner/estimate, schedule planner, layout manager, work package manager. The interface enables dashboard view, but with all the data complexity and limited functions of the 3D view it lacks flexibility.

Regarding the 4D, the software essentially allows to connect the project information elements, where the planning is issued from connection to the planning applications, yet has its own planning function with possibility to edit activities. Vico Control enables location-based planning, visualization and flow control, Gantt chart and CPM, can illustrate a plan over a longer period. In addition, it also enables LOB schedule. The scheduling visualization allows hierarchical division at the planning levels with different degree of detail.

The 4D rendering implements various color codes to enhance understanding. The software may be further adapted for Lean construction with implementation of the option for digital levels of LPS planning and task requirements control, in addition to the implemented production rate of each activity related to the assigned resources and crew. The tool's use is extended to mobile use for reporting the activities on a tablet, which allow better connection with the construction progress, but does not always the use of a 3D model for all uses. A study by Chen and Tang investigates BIM and integrated management workflow implementation for maintenance planning, and compares the existing commercial 4D and 5D BIM applications, and chooses Vico Office as a tool enabling 5D BIM use, modeling and secondary development for facility maintenance (Chen and Tang, 2019). Thus, today there is a need for the tools enabling all project phases and digital continuity of data.

In summary, a variety of commercial solutions are available to AEC professionals offering focus on different tasks and supporting different design, construction and project management activities. The presented emphasis of Navisworks, Synchro, VisiLean and VicoOffice selected features does not seek to compare them but to highlight the main uses of 4D and approaches to 4D tools design (Table 10).

Ultimately, 4D applications and planning tools face similar challenges in research of the balance between the need to provide functionalities, to operate different types of information, and at the same time provide the users with clear and adapted visualization of the project model. Also, the digital BIM workflow and integrated teams must find the utility of such applications use for planning and for construction. Not only the working view, but also a dashboard view is required to support project progress tracking and communication with the 4D simulation as the mediator. Moreover, too advanced software and interface may limit the uses only to selected number of experts, thus hindering transparency and collaboration.

The future research of relevant and useful functionalities for the novel tools would be oriented towards the new generation of BIM tools, representing rather not stand-alone software solutions, but emerging in the category of on-line applications for collaboration, for data and skills integrations, than standalone desktop software products.

Table 10 4D BIM solutions features summary

| | | Navisworks | Synchro 4D | VisiLean | VicoOffice |
|--------------------------------|-----------------------------|-------------|-----------------------------------|-------------|------------|
| Schedule representation | Gantt | ● | ● | ● | ● |
| | LOB | - | ● | - | ● |
| | Lean | - | - | ● | - |
| 4D use | Visual communication | ● | ● | ● | ● |
| | Scheduling | ● | ● | ● | ● |
| | Clash Detection | ● | ● | - | - |
| | Safety Management | - | - | ● | - |
| | Site Layout & Environment | ● | ● | ● | ● |
| | Constructability Management | ● | ● | - | ● |
| | Monitoring | ● | ● | ● | ● |
| | Weekly planning | - | ● | ● | ● |
| | | | | | |
| Construction management | Resources | ● | ● | ● | ● |
| | Requirements | - | - | ● | - |
| | Teams | - | - | ● | - |
| | Quantity take-off | ● | ● | ● | ● |
| | Scenarios | - | ● | ● | ● |
| | Risks | - | - | ● | ● |
| | Reports | - | ● | ● | ● |
| Interface | Desktop | ● | ● | ● | ● |
| | Mobile | - | ● | ● | ● |
| | Dashboard view | - | - | ● | ● |
| Interactions | Single user | Single user | Single user | Single user | |
| Collaboration type | Cooperation ^{xii} | Cooperation | Distant synchronous collaboration | Cooperation | |

^{xii} As a collective activity which relies on sharing resources, but does not necessary encompass collective and synchronous contribution from the actors

Interface and interactions design of commercial solutions for lean planning

Various commercial digital solutions are available for construction planning and management supporting lean principles and lean tools implementation. Most of them are rather focused on planning and do not extend to BIM project models yet. However, their interfaces seek clear visualization and equal ease of use by project managers authoring planning and by trades team members. Therefore, the interface and interactions design enhance these functions. Moreover, the tools propose digital platforms enabling distant collaborative project development and updates, which puts the data continuity and accessibility in the core of collaboration.

For example, *QLean*³⁹ proposes a commercial cloud-based platform for digital pull planning enabling co-located and remote planning and tracking of the project tasks. The interface presents a reference to a digital “sticky note” system with minimalistic interface and interactions (Figure 55). *Touchplan*⁴⁰ proposes a platform for lean construction management enabling digital pull planning, master schedule alignment, look-ahead planning, real-time updates and variance reasons. This solution represents one of the powerful digital tools. It enables interactive planning with multiple levels of detail and construction crew management. The planning activity interactions are designed not only for the desktop users, but also for the mobile users or for the large screens with zoom-in and zoom-out interactions enabling different levels of planning precision. It also proposes a dashboard view with progress and PPC analytics. However, the BIM connection is not yet available.

LetsBuild proposes a platform with GenieBelt⁴¹ (Figure 57) and Aproplan for construction management enabling scheduling and progress tracking with focus through filters on visualization of only relevant information. It also supports the import option from the scheduling tools and visualization and connection to the project plan. The platform also proposes functions supporting lean principles implementation in construction.

There are also solutions designed for project management yet allowing collaborative planning. *Plannerly*⁴² is an online environment for collaborative BIM management with modules for BIM Execution Planning and visual BIM scopes defining levels of information and BIM uses. It also has the verification modules for compliance checking, allows 3D coordination, progress tracking and proposes the use of a simple browser-based task editing tool to the task teams (Figure 58). Despite the interface design for a single user interaction, it represents an example of a tool, with an interface design which considers the remote collaboration and proposes high interface interactivity, which allows quick interactions with the system, and visualization.

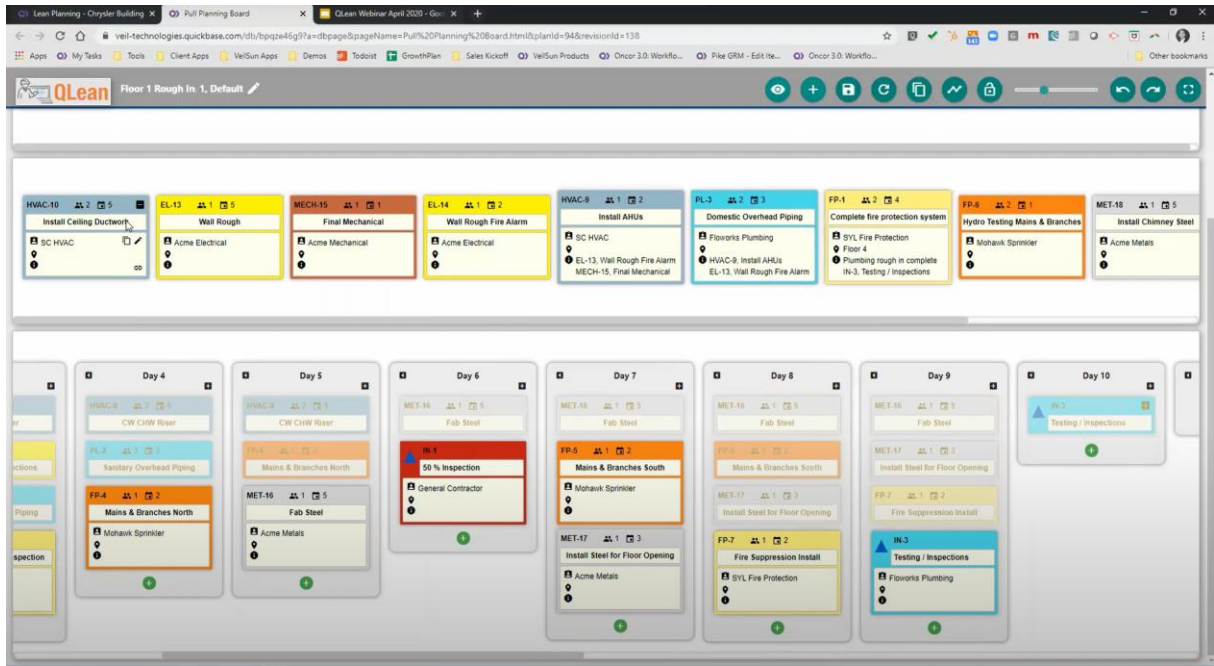


Figure 55 QLean interface visualization of the construction tasks (source VeilSun, Inc. "Virtual Pull and Project Planning from VeilSun"⁴³)

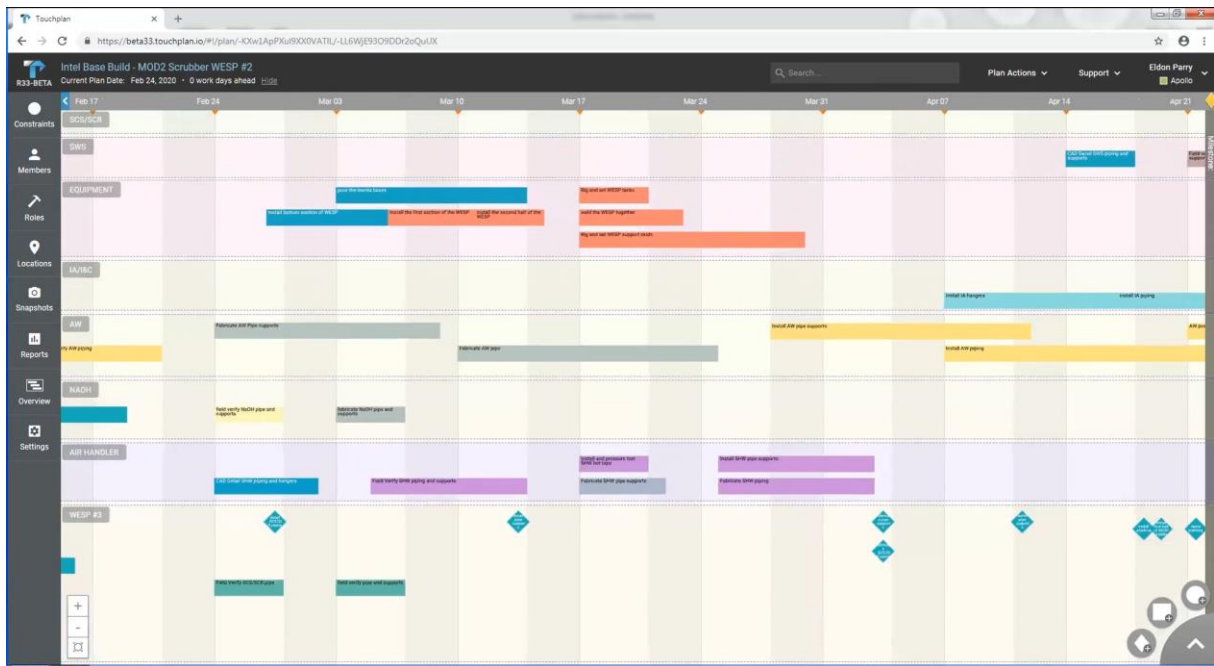


Figure 56 Touchplan interface (source Case studies "Apollo Mechanical"⁴⁴)

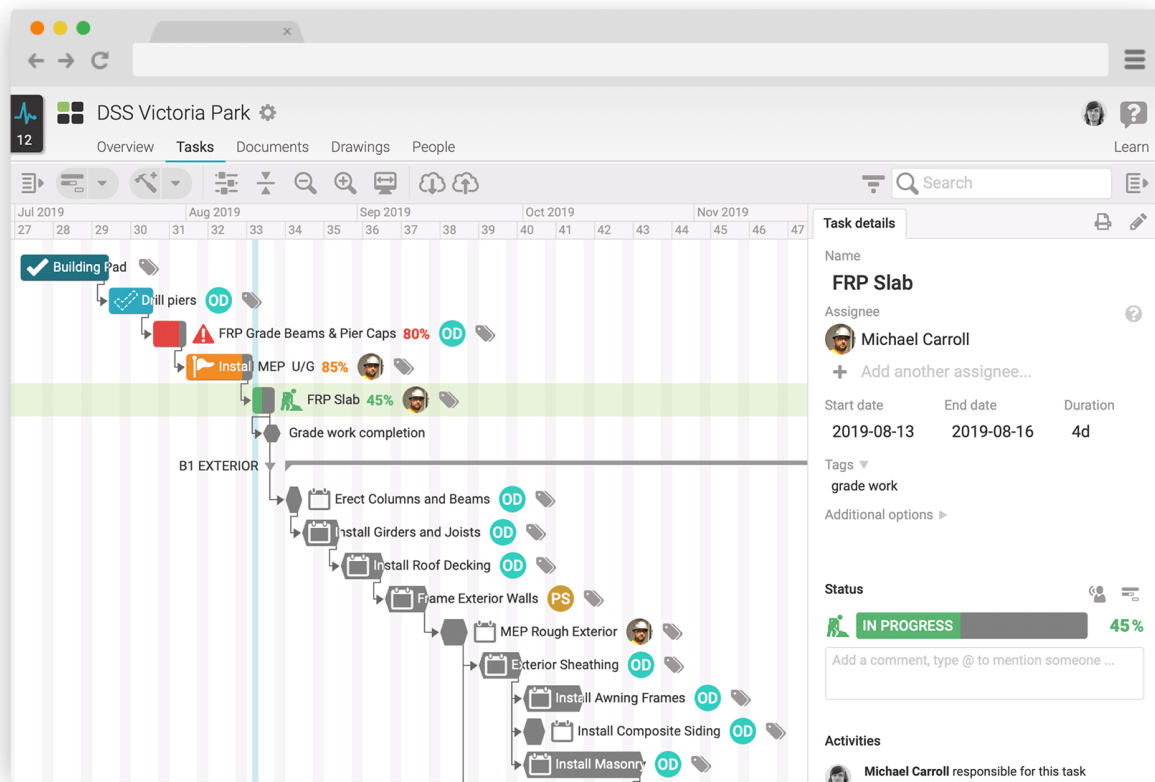


Figure 57 LetsBuild GenieBelt for planning interface (source <https://www.letsbuild.com/progress-planning/lean-planning>)

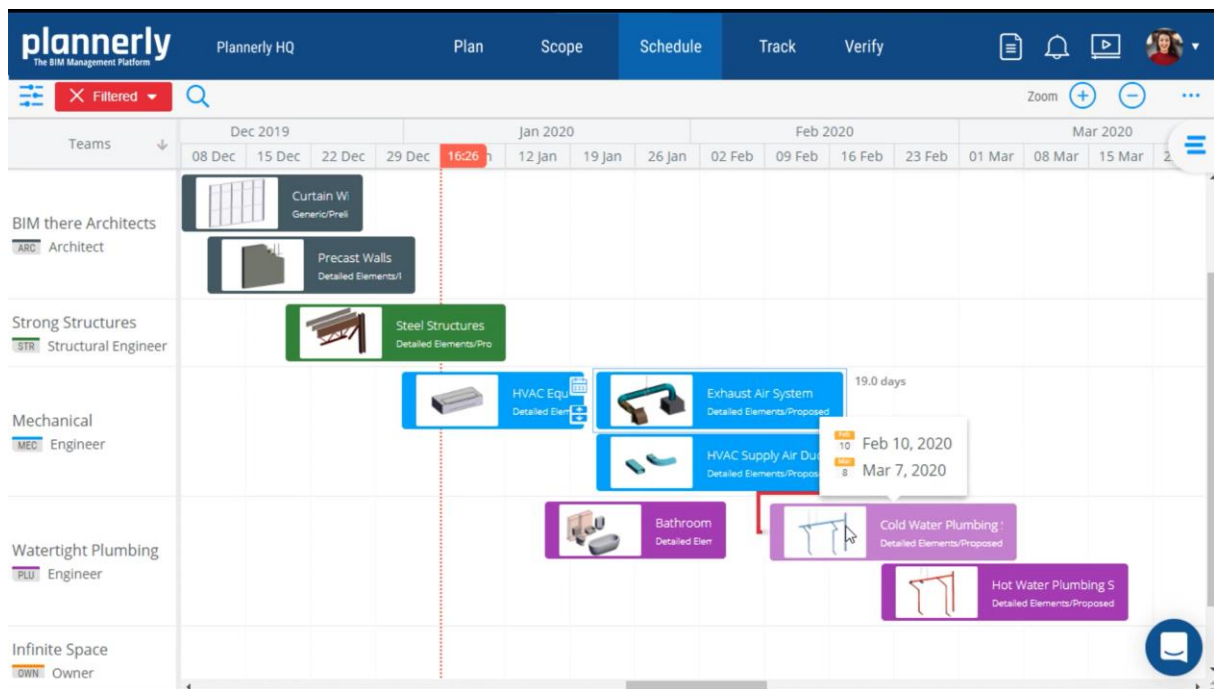


Figure 58 Plannerly schedule interface (source <https://www.plannerly.com/schedule/>)

BIM and Lean solutions: requirements identification and development

One of the early studies by Sriprasert and Dawood investigates the issues of information visualization and multiple constraints for collaborative planning and control and identified the development

requirements for an efficient digital lean production system which include among others, *the need to consider three different levels of planning: project, processes, assignments*, as well as the need to foster digital project workflow. The study also developed a Lean Enterprise Web-based Information System for Construction – *LEWIS*, which represents one of the early efforts to propose a digital tool for Lean principles implementation (Sriprasert and Dawood, 2003).

Further research towards digitally supported lean scheduling and construction management displayed on large boards, by Sacks et al. identifies the *need to make the state of construction process transparent* for all project team members with effective information flows between management and production. Therefore, the study analyzes process visualization and pull flow control, and foresees the potential benefits from BIM and *4D visualization tools synergy with Lean construction requirements*, such as production planning, management, control, pull flows, to assure process transparency and respond to the updates (Sacks et al., 2009).

Thus, as one of the solutions, a prototype enabling controlled work-in-progress “CONWIP” including the project workflow model and on trade workflows model proposes a digital solution for the visual management of production (Sacks et al., 2009). The study also suggests that further development of the digital tools would require for a design of efficient user interfaces and allow the data and updates inputs from the construction companies.

Following this line of studies, further research efforts identify the requirements for a development of the BIM-based Lean production management system, which must be considering:

- *visualization of process, product and methods,*
- *visualization and computation of work packages and task progress status;*
- *provide a support for planning, negotiation, commitment and status feedback*
- *provide a stable workflow and plan;*
- *features enabling implementation of pull flow control;*
- *provide project summary for continuous improvement (Sacks, Radosavljevic, et al., 2010).*

They also emphasized different aspects related to the Master planning, Lookahead planning, Weekly production control levels of detail (Table 11). For example by illustrating the change of relationships with the resolution becoming more detailed, and shifting the approach to the goals achievement (Sacks, Radosavljevic, et al., 2010). Therefore, the digital tools must support such dynamics.

Table 11 Aspects of construction planning and control according to level of planning (source (Sacks, Radosavljevic, et al., 2010))

| Planning level | Master planning | Lookahead planning | Weekly production control |
|--|--|--|--|
| Aspect | | | |
| Resolution | Milestones | Work packages/ activities | Tasks/assignments |
| Goals | Define contract packages | Make work packages ready; release constraints | Manage flows of people, material, work, information, etc. |
| Methods for definition of planning unit | Top-down division of project duration | Top-down division of milestones into activities | Bottom-up aggregation of parts into a task |
| Tools and measures | Contract terms; critical path method; and process optimization | Critical path method; constraint release; maturity index; and line of balance scheduling | Pull priority; negotiated team coordination; and maturity index (provided in KanBIM) |
| Relationships | Contractual | Hard technological constraints (such as FS); resource leveling and space conflict resolution | Flexible working relationships/resource and space coordination |
| Primary plan and responsibility | Construction manager | Construction manager in consultation with trade team managers | Trade team leaders and managers |

Thus, the study proposes *KanBIM™* framework and prototype for planning and control process, which enable the joint implementation of the project 3D BIM model linked to the Kanban for more efficient and visual construction planning and production control based on the Last Planner® system (Sacks, Radosavljevic, et al., 2010), which becomes a “... *management information system comprising procedures, software and hardware designed to support lean work flow control on construction sites.*”(Sacks et al., 2011). The evaluations of the system by AEC professionals emphasize the need for an *integration of sub-contractors into the detailed planning process*, and the *need for efficient visualization of the construction processes* information for successful production management (Sacks, Radosavljevic, et al., 2010). Further evaluations of *KanBIM™* implementation at the field tests report its usefulness for the superintendent and high usability for the construction crew leaders (Sacks et al., 2011).

Thus, *KanBIM™* places the project BIM model not only into the center of the user interactions of the interface (Figure 59), but it also forms the digital core for the processes. One of the primary functions allows for task status updates (Figure 60). Such information is essential for production management, yet may *present challenges to the clarity of the project information visualization* (Sacks et al., 2013). The study reports that the relevant, useful and clear information visualization is challenging, moreover the interactions with the information must also be easy and accessible to all construction teams, for example with the use of the large-scale touchscreens enhancing collaboration activities.

The proposed prototypes of an integrated production management system benefit from BIM and Lean joint implementation to enhance visualization quality and construction activities efficiency and establish the basis for the further investigations upon their synergy and development of useful and usable interactive tools.

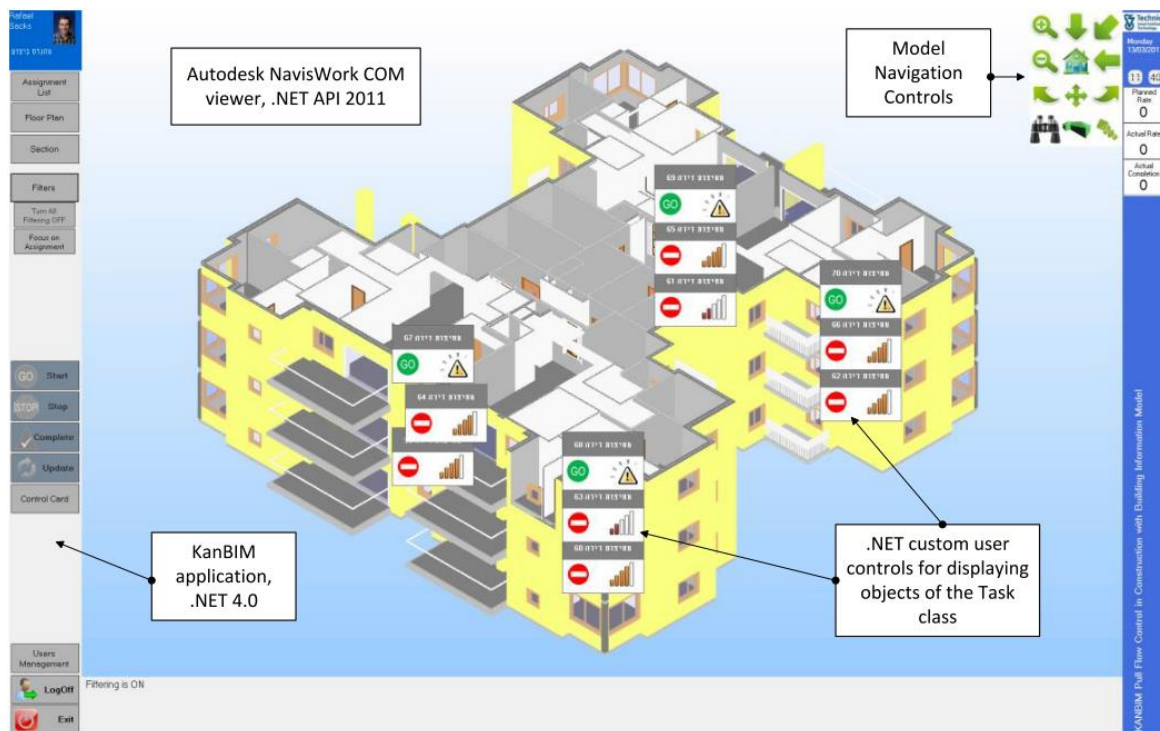


Figure 59 KanBIM primary interface, showing the .NET 4.0 application, the embedded Navisworks COM viewer, the custom task controls overlaid on the model, and the model navigation controls (source (Sacks et al., 2013))

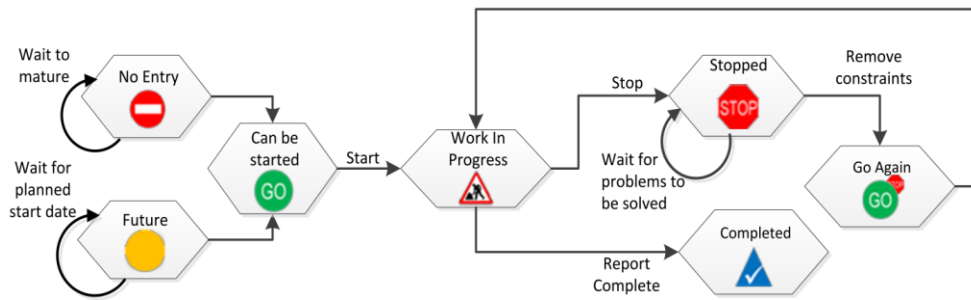


Figure 60 KanBIM™ task status cycle (source (Sacks et al., 2011))

Already mentioned above research, also proposed a summary of requirements VisiLean prototype evaluations enabling BIM and lean construction use for production management. VisiLean places Phase schedule, Lookahead schedule (Figure 61) and Weekly Planning and execution in the prototyping, and proceeds with uniting 3D and schedule information in the view. The visualization is also provided by icons and tasks status indicators (Dave, 2013). In order to structure the prototyping, Dave outlines that system requirements encompass a variety of functional, technical and interface requirements, and uses the following categories:

- Process and Product visualization available on site;
- Supporting constraints analysis and management;
- Supporting collaboration, work negotiation and communication of the project team members;
- Enable “pull” flow control and plan stability (Dave, 2013).

From the prototype evaluations with users the study concluded the usefulness of the proposed digital Lean *solution that offers an integrated system*, and emphasize the users feedback on the *need for an intuitive in use solution* not requiring extensive training, supporting *BIM integration and collaborative planning workflow* (Dave, 2013). Moreover, the users also suggested the need for a dashboard interface with real-time updates; the need for a system with several kinds of user profiles having different level of access to control and management; the need for automation of notifications for the weekly planning meeting preparations.

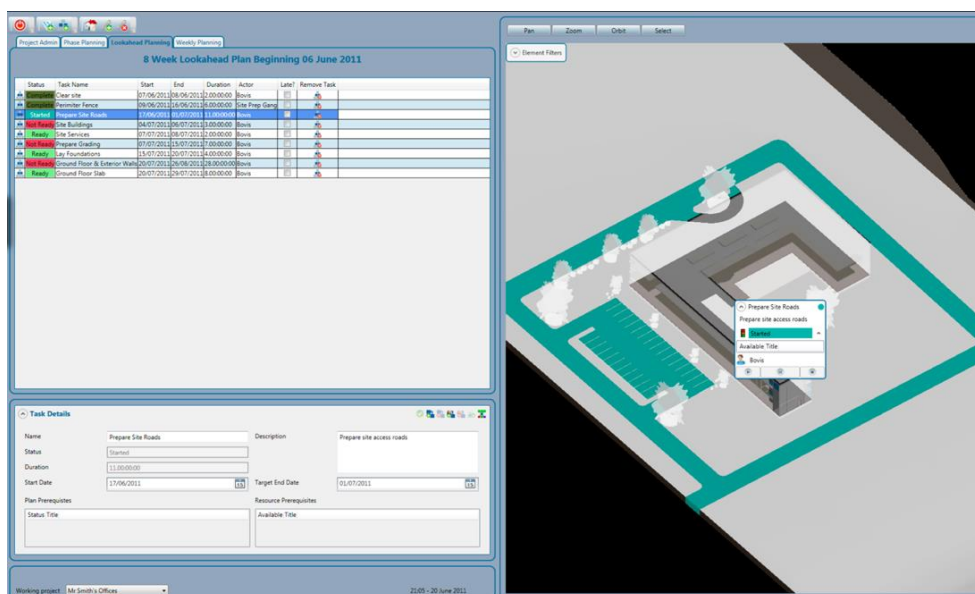


Figure 61 Illustration of VisiLean interface: lookahead planning (source (Dave, 2013))

Guerriero et al. outline *the lack of integrated information management tools and the need for a collaborative, iterative and modular design of such tools*. They thus present a research aiming towards an integrated IT-solution with *Smart Construction Planner*[®] (Figure 62) enabling digitalization of Lean methods, and creating the interactive environment for collaborative location-based planning, decision-making and construction management (Guerriero et al., 2017). The prototype illustrates the idea of a connected construction site with *collaborative planning and requirements management; dynamic site layout planning; on-site material delivery planning and tracking*. It also presents the features enabling *4D BIM uses and Lean construction tools*. For example, the 4D visual communication is enabled by a feature of “To do/Doing/Done 4D visualization” fostering collaboration and understanding and relying on lean visual management and Kanban use. Thus, the study outlines the need for efficient visualization of the project data, 4D simulations, and construction progress with an easy to understand dashboard. Another example of the 4D BIM use, is 4D scheduling with the help of collaborative planning, LPS and location-based planning which is mediated by a board with a multi-touch interface and extended to a mobile application, which assures the communication with the construction team members.



Figure 62 Smart Construction Planner (source (Guerriero et al., 2017))

Hua and Schwartz present the *visual management-based make ready tool* in a case study with LPS[®] implementation, and report on the difficulties or limitations on efficient implementation due to *lack of training in LPS[®] teams*, and report as well “*incomplete or incorrect implementation*” due to *a lack of time for successful implementation* of LPS[®] which brings change to project management and operations (Hua and Schwartz, 2021). In the case study the project team members used analogue visualization tools such as boards with Master Schedule, Phase Schedule, Make Work Ready plan, Weekly Work Plan.

The implementation *fostered collaboration and stakeholders’ involvement*, as well as regarding the project meetings it augmented productivity by providing the *LPS[®] structured routine, by improving the team focus on LPS[®] objectives, and optimized meetings duration*. Hua and Schwartz also addressed the issue of optimization of visual management control with design and development of a Make Ready tool

for Weekly Work Plan and Constraints removal. The tool improved visualization and control of project tasks and constraints management, as well as facilitating the collaborative interactions and use of collective intelligence.

The study reports that project team members found the visual management tools particularly useful and relevant to LPS® use, and that they assist with “... *anticipating problems and improving collaborative decision-making, rather than firefighting and solving administrative issues.*” (Hua and Schwartz, 2021). However, the researchers identified *that analogue time charts updates were laborious*, the data was not complete or readable, as well as accessible only at one physical location on construction site. Hua and Schwartz outline that the use of analogue (physical) boards hinders collaboration efficiency and LPS® implementation due to the limitations of analogue supports but exceeded with highly adaptive digital solutions. In addition, they suggest that the *use of digital visual management tools would foster the better adoption of LPS®, collaboration, dataflow and workflow efficiency* (Hua and Schwartz, 2021).

Thus, they proposed a software (Figure 63) which enables users to:

- “Copy/paste sticky notes that, after few weeks of work, are often the same or just a variation of old sticky notes,
- Adjust planning with the drag-and-drop function,
- Duplicate entire boards or sequences of work to create alternative scenarios,
- Copy data from a low-detail planning to a higher-detail one.” (Hua and Schwartz, 2021).

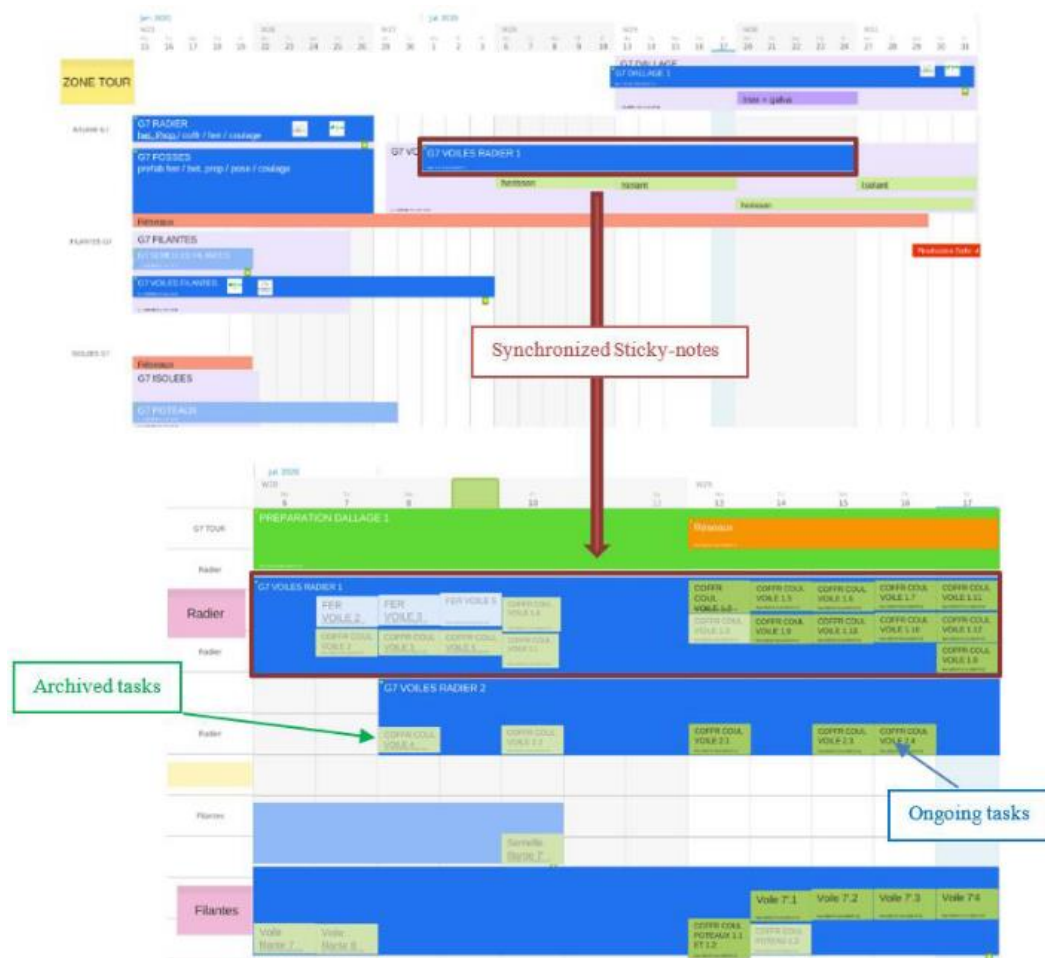


Figure 63 Illustration of Phase Schedule to Look Ahead Plan to Weekly Work Plan (source (Hua and Schwartz, 2021))

Key points of 2.2.1

Overview of BIM and Lean collaboration solutions

- 4D BIM model proposes a variety of different features and uses, with the emphasis on viewer-modeler-checker functions. The tendency towards more integrated and interoperable project data flow also influences the 4D BIM tools features, fostering emergence of cloud-connected solutions enabling both distant (remote) and co-located collaboration. However, the technical and social efforts are required to foster benefits of the integration.
- Different approaches investigated technical and social aspects of BIM tools implementation for collaboration mediation, proposed frameworks for project meetings analysis including tools for activities and interactions description. The studies confirm the benefits in BIM and 4D use for decision-making, yet outline the need for digital data continuity, for efficient and relevant interactions, and suggest use of touch-supports to foster interactivity.
- Commercial 4D BIM and Lean solutions developed to answer the demands from the industry to achieve interoperability, enable modeling, planning, clash detection, construction production management, and as established products provide the users with many functions. However, their design and core features do not always enable the efficient implementation of 4D BIM uses, data integration, nor provide interfaces for interactive and collective decision-making. The synergy between BIM and Lean principles implementation is supported only by VisiLean platform (B1, B3).
- The research advancements investigating the use of BIM, lean, collaboration and interactions identify various requirements for efficient digital tools and for supporting protocols development, which provide background for our research. They identify issues concerning the complexity of the joint use of various kinds of information, of synergy of 4D BIM uses and Lean principles, of need for clear data visualization, processes transparency and efficient interactions.

2.2.2 Emphasis of the requirements for 4D-based collaboration tool and user interactions

2.2.2.1 Social: transformation of processes, organization and roles

Need for practices and approaches relevant to the digital and integrated practices

Digitization and BIM adoption, integrated approaches and Lean construction have contributed to the various advancements and challenges of AEC (1.1.2.3; 1.1.3.2; 1.3.1.1; 1.3.1.2). With the design tools, construction planning and project management methods advancing, the focus is on optimization, digitization, collaboration and integration. Innovative tools for design, management and construction appear as solutions to existing problems or opportunities for new features transforming the digital core of the work on a project, and they are transforming the processes around it. Thus, such ***transformations reveal the need for practices, encompassing new skills, competences, roles, protocols and collaboration scenarios, and for the approaches to project design and management which would be most relevant to the digital and integrated project delivery.***

From a socio-technical perspective collaboration is influenced by a complexity of factors, but to assure its efficiency there is ***the need for an organization to provide a social structure***, which will be fostering knowledge accessibility and sharing, and considering ***trust, location and motivations*** influence on the collaborative activities (Søndergaard et al., 2007).

The transformation may be challenging in many ways, requiring efficient adaptation from not only the tools and processes, but from the people as well. Lessons learned from BIM and IPD Implementation into construction project management, report it is necessary to ***have a person in charge of BIM in every firm*** involved into the project to assure and improve the flow of information (Erazo et al., 2020).

Even from the beginning of the project development, the project program information already commences to shape the digital project information core. Kiviniemi proposes an interface to implement ***project program requirements*** in building information at the earliest design phase (Kiviniemi, 2005). Further, digital design tools help to maintain the link between pre-design project requirements and the project design (Penttilä, 2006), and moreover, with the optimization as an aim, they offer features for control and automated analysis (Siala Chakroun, 2019). Thus, even from such early stages, not only the tools but the work practices and collaboration approaches must be set.

Further, the design process adapts as well, shaped by BIM protocols and supported by BIM managers, coordinators and all the stakeholders of design. Moreover, with more integrated and collaborative approach, the construction professionals contribute to the design choices as well. Finally, the construction phase practices change as well, since a production management system which integrates project (product) and construction (processes) must consider the features of ***visualization, integration, and synchronization*** in the same system (Dave, 2013). A variety of new tools support the construction activities, for example the scheduling tools become also ***compatible with monitoring methods*** (Ratajczak et al., 2019).

Need for digital data continuity, accessibility and interoperability

The aim of design automation is to provide integrity and consistency of project design data (Eastman, 1979). BIM implementation fosters a variety of changes as well as it brings benefits. However, efficient functioning and use of BIM for design and collaboration must be supported by digital data continuity, accessibility and interoperability.

There is a need for data connections and continuity supporting various skills and knowledge which may benefit from nD BIM use (Boje, Guerriero, et al., 2020). Document management systems must ***not only support the design and document flow but integrate into the decision-making***, to be part of a more comprehensive system supporting the digital continuity and group interactions.

Digital data continuity without information losses and redundancies and integrating all the project information is beneficial. Often, during the meetings sketching, annotating, brainstorming are not supported as well by digital tools as decision documenting, but rather result in a paper trail of various documents (Dossick and Neff, 2011). Thus, there is a ***need to include 'paper-based' information into the project dataflow***, to assure continuity and preserve the made decisions. The early definition of BIM protocols and information management is required with precision and expertise, since it sets the basis for the project data flow and integrated team collaboration (Ashcraft, 2012).

Also, even the efficient visualization or interaction with digital documents at the decision-making session, sometimes does not keep a direct connection with the BIM model, causing the ***need to reintegrate the results of a decision-making session*** (notes, tasks, modifications, new data). Moreover, the editing of such reports may become a cumbersome task. The constraints for a synchronous collaboration environment identified by Isikdag and Underwood suggest that all the project ***updates must be available for all project team members and in real time*** (Isikdag and Underwood, 2010), which may be also supported by the digital dataflow continuity.

The accessibility of the project information is also essential for efficient collaboration, in addition to the continuity. The technological solution integrated into project meetings as a mediator must also ***sustain the link*** to BIM model, to digital project management methods and accompanying processes. Moreover, with a digital technology integration, the project maintains design integrity, and the project team members would benefit from an ***easy and distributed access*** to project documents (Fischer and Kunz, 2004).

From the perspective of construction management, the ***access and real-time dynamic updates to various project documents and information*** (material procurement and delivery, equipment hire and availability, labor availability, space availability) are necessary for efficient decision-making (Dave, 2013). An efficient digital production management should provide continuous access to digital information, which would be more frequent than once a month or a week (Sacks, Korb, et al., 2017). An access to the consistent project information is essential for all disciplines to be efficient as an integrated team (Fischer et al., 2017; Ch.3).

Data interoperability is also essential for a BIM-based project, benefiting from the variety of inputs from different disciplines. Ashcraft highlights the ***need for interoperable information*** stored in a secure way with short access path (Ashcraft, 2012). In addition to the need to access technology, there is also the need to consider the social elements, such as business strategy, management of external relationships, collaborative business processes, organizational structures, employees and work culture, information systems (Grilo et al., 2013). Steinmann et al. emphasize four levels of interoperability requirements: ***technical, syntactic, semantic interoperability, functional interoperability*** (Steinmann et al., 2016). Therefore, interoperability encompasses even larger scope than just digital project data interoperability.

2.2.2.2 Technical and social: digital collaboration environment setting

Need to enhance BIM and digital supports use for collective decision-making

Before the broad diffusion of BIM and digital collaboration tools, Lee et al. summarized the efforts from the research community in developing a vision for new more integrated environments and for a new nD BIM modeling tool. They consider a system encompassing technology, people, business strategy aspects which are connected to the organization of work. Lee et al. report that "... the proposed tool must be *imaginable, desirable, feasible, focused, flexible and communicable*" (Lee et al., 2002). By extension, such characteristics may be transferred as well to the decision-making, and the approaches enabling user-participation, focusing on usability, and proposing integration could assist with their implementation. Various studies have explored the subject of BIM collaboration (1.2.1.2; 1.3.2.2), and established the basis for understanding the phenomena occurring during AEC collaboration, and emphasized the technical and social requirements to enhance efficiency of a digital collaboration environment.

Project stakeholders may be working on a single collaborative BIM model, or on specific professional parts of the BIM model and assemble all the data into a single model later (Steinmann et al., 2016). Then, when collective design and modeling is finished, the project development comes to a 'decision-making point.' The decision-making calls upon collaborative intelligence, however there is a need for development of technological and methodological solutions for a fully collaborative digital system which would be integrated into the BIM process and assure a continuity of data exchanges. Today, at the decision-making session the continuity is not integrated into common practices and is "interrupted" by printed documents or handwritten notes.

Since the adoption of BIM and its use for design development, it brought a variety of benefits. However, since its primary use is focused on design activities, the development and implementation of the tools and methods enabling its use for value engineering took time. Today, there is the need to enhance BIM and digital supports use for collective decision-making. Project teams use BIM as an information source for design development and value engineering, thus they need an *efficient digital collaboration environment* (Achten, 2002), with *quality interactions* (Tory et al., 2008). In addition, in a wide range use, *interoperable data formats have not integrated the schedule dimension* into a single model connected with 3D (Kassem et al., 2014).

Decision-making quality may be improved in various ways. Fischer et al. analyze feedback from collaborative design mediated with digital artifacts to identify requirements for socio-technical environments *fostering group creativity*. They outline the importance of *collaboration for better creativity*, and for better understanding. The *human interactions are essential for social creativity* (Fischer et al., 2005). They also emphasize that socio-technical settings can amplify collaboration outcomes, for example, by allowing users to manipulate "shareable boundary objects on the shared space" which mediate and foster communication and user engagement. BIM use may be in the core of such socio-technical setting.

A study by Whyte et al. investigates visualization of relevant project knowledge and documents through observations of two use cases of project-based work. The study describes the observed use of diverse types of visual supports by project teams, among which project outcomes were summarized and discussed through:

- *strategic project timelines (goals, business, and relationships);*
- *Gantt chart (scheduling activities);*

- *progress charts (progress and revenue generation, assessment of risks);*
- *3D CAD models (Whyte et al., 2008).*

The described variety of visual supports illustrates a ***need for adapted visual supports to decision-making situations that would highlight relevant elements*** of project information. Even though the study does not investigate 4D or lean scheduling, it suggests that for different representations of project time management information there is a need for different focus and levels of detail (Whyte et al., 2008). The configuration of a BIM-based collaboration tool must consider the constraints. The efficient collaboration and interoperability tools must help avoid project information losses, optimize workflow, avoid redundancy of tasks, and maintain the link to BIM data storage.

Further, with the evolution towards more collaborative and integrated approaches, the project data still represents the core of the project development, thus there is ***the need for integrated information use to support decision-making, available for at all project levels*** from project management to construction activities. Such use would also enable exploration of multiple alternatives and emphasize project constraints (Fischer et al., 2017; Ch.10). Moreover, collaboration encompasses not only logical and structured processes, but also the collaborative conversations “... *require informal, active and flexible visual media.*” (Dossick and Neff, 2011). Thus, the digital tools must support such activities as well.

Need to enhance interactivity, communication and mediators for collective use

Various studies experimented with different configurations of equipment enabling collaboration of AEC professional at the project meetings, mediated by various digital environment solutions (2.1.2.3, 2.2.1.1, 2.2.1.2), and emphasize the need for relevant and adapted collective use mediators, communication and interactivity. Such need may be answered with the ***relevant device choice, and collaboration application interface and interactions design***. Thus, in our study, activity mediators are regarded as devices providing access to BIM application providing user friendly interface and collective interactions.

The study of AEC collaboration with digital artefacts by Tory et al. observed limitations of medium size vertical screens and available at the time software for use as collective activities digital mediators, since they were ***not providing enough display space*** to avoid project documents overlap obscuring one another, therefore impacting the quality of visualization and interactions at the project meeting (Tory et al., 2008). In addition, despite the same study observations of some advantages of paper-based meeting mediators, the use of digital supports still should be beneficial in the future through simplified navigation and interactions adapted to individual and collective use (Tory et al., 2008), highlighting the need for interfaces adapted to group use. Thus, to avoid this phenomenon we investigate a ***use of large-scale screens and a software providing easy “scaling”*** of the documents through touch-interactions.

A case study indicated that ***interactive devices support formal and informal collaboration activities***, with a vertical display type for presentation-related activities and tabletop display for many collaboration scenarios (Mahyar et al., 2010). Fischer et al. outline the importance of the traditional ‘wall space’ use to visualize and share team status, planning, and goals, thus uniting the project team and emphasizing the scope. They also outline the use of digital supports as SMART Bards and BlueScope walls that provide an interactive digital multi-user collaboration environment, stating as advantages: easy interactions, easy access to information since ***“Information that is visible has greater impact than information that is out of sight, regardless of how easily it could be retrieved.”*** (Fischer et al., 2017; Ch.14). Therefore, the digital collaboration environment must provide with vertical and horizontal displays.

Moreover, regarding in particular BIM and Lean synergy, Dave et al. outline the importance *of participation of all project key members in BIM-based collaborative planning at the lean scheduling meetings*. The study suggests the use of Smart Boards and virtual collaboration platforms to support collaborative interactions. It also suggests that the *use of mobile technologies like tablets and smartphones* to support the predictability and waste reduction (Dave et al., 2013). Such requirements would foster the use of the integrated project data and enhance its digital continuity.

Fischer et al. describe the cost and budget tracking dashboard implementation for a complex integrated project use case. The weekly dashboard updates provided access to the project progress information and foster more informed decision-making (Fischer et al., 2017; Ch.10). Ghaffarianhoseini et al. outlined the potential of BIM use for a project, to integrate many kinds of data from design, construction, management and manufacture *into one fully integrated facility dashboard* (Ghaffarianhoseini et al., 2017). The use of dashboards is essential for survey and analysis, communication and learning, it is also used in Integrated project delivery and Lean construction, thus the choice of the digital tools must enable such activity.

As outline Relekar et al. the recent technology advancements help to focus the development on innovative user-oriented applications (Relekar et al., 2021), thus they facilitated the design of the interface and interactions.

The interface quality is essential for efficient collaboration, since the theoretical explanations of factors influencing the decision-making by humans do not always rely only on weighing the available options and on reasoning, but on 'good enough decisions' of simple frugal heuristics (Preece et al., 2015). From design perspective an interface adapted for such action as quick thinking and learning would rely on "*...effective design strategy is to follow the adage 'less is more' rather than 'more is more,'*" (Preece et al., 2015).

An analysis of the existing commercial solutions from the interface quality perspective and *perceives the need for training and experience to use the 4D or construction management tools efficiently as a critical issue that hinders their usability*, especially for complex projects where the whole team must be operational to use the tools (Dave, 2013). Therefore, for a 4D collaboration solution the interface design and proposed interactions must offer to the user a possibility of quick learning.

Moreover, the interface of a software or an application for 4D-based collaborative decision-making should also consider the complexity of project models; thus, it would adjust to the specific uses of every BIM level of development. The users (AEC professionals) with different *disciplines background usually have different usage patterns*, thus a collaboration system design must present a user relevant interface (Singh et al., 2011). Thus, to enhance interactivity and collaborations an interface must *consider those different backgrounds and* seek to provide *equally easy and quality usability* to all users (meeting participants), regardless of their experience and level of understanding of the project. Also, the domain of interface design and ergonomics suggests to implement the mechanisms *as mutual awareness of other users' actions*, or *degree of user control* over the actions within a system, and *availability of information*, are required for quality interactions (Yuill and Rogers, 2012).

We propose to rely on *Natural User Interfaces (NUI)*, which offer the ease of access and brief learning time with the interface's tool (Steinberg, 2012), and enhances project documents convergence with the ease of interactions (Whitney, 2013). The collaboration of the project team should not be hinged or limited by the digital mediator for collaboration but empowered.

Most of the collaboration solutions offer an interface that *does not enhance multi-user group interaction*, since they are not specifically developed to mediate project meetings or use for decision-making. The interface design often relies on “user persona” as a tool requirements identification and development. However, Kuutti and Bannon, outline that: “*The individual user cannot be the unit of analysis - user needs are not a homogenous mass, but consist of sets of needs, differentiated and separated from each other depending on the practice.*” (Kuutti and Bannon, 2014). Thus, we rely on an approach considering the needs of the project team as a “collaboration group persona” (4.1.1.1).

Various studies analyzed AEC collaboration and occurring interactions, and emphasized the types of interactions (Table 12). Such as initial studies by Tory et al. which outline the types from CSCW analysis of collaboration session and the importance of *quality interactions* (Tory et al., 2008); or the work on interactions design by Preece, Sharp and Rogers (Preece et al., 2015) through the approach of HCI; as well as the more recent study by Mehrbod et al. of collaboration sessions extending the work of Tory et al. with the detailed collaboration enabled by different physical (paper, sticky notes) and digital (PDFs, picture, Revit, Navisworks) artefacts observations and analysis the interactions with categories (Mehrbod et al., 2019). Moreover, Erazo et al. analyzed the requests for project information during collaboration and decision-making, where the need for confirmation represents most requests, and only highlights the importance of information accessibility and quality visualization (Erazo et al., 2020).

Table 12 Summary of studies proposing collaborative interaction types

| Study | Approach | Interaction levels |
|----------------------|---|---|
| Tory et al., 2008 | CSCW, Interaction taxonomy | <ul style="list-style-type: none"> • gesturing • navigation • annotation • viewing |
| Preece et al., 2015 | HCI | <ul style="list-style-type: none"> • instructing (users issue instructions to a system) • conversing (users have a dialog with a system) • manipulating (users interact with objects in a virtual/physical space by manipulating them) • exploring (users move through a virtual environment or a physical space) |
| Mehrbod et al., 2019 | Design coordination, CSCW, Interaction taxonomy | <ul style="list-style-type: none"> • preparation (model integration, clashes review, color code, lookup) • annotation (sketch, erase, air draw, modification) • navigation (change view, zoom, switch, save/load, exchange trade) • recording (update, snapshot, notes) |
| Erazo et al., 2020 | IPD, ICE, requests for information | <ul style="list-style-type: none"> • confirmation (no certainty on information/detail) • improvement (an added value proposition) • design Issues (engineering incompatibility issues) |

These interaction types address the specific study goals and describe the phenomena from different perspectives. Yet, the essence of their implementation illustrates different relations between the actor and the mediator. Moreover, despite global tendencies towards globalization the users cultural context influences the uses. Smith et al. investigate the limitations of application of HCI and UCD approaches in variable local cultural contexts, outlining that the cultural context may influence organizational structure, practices and activities, with need for “*cultural and linguistic adaptability of systems*” (Smith et al., 2010). Thus, such criteria must be considered during the interactions design and evaluation.

Collaboration and decision-making at the meetings require not only shared project views, but also a *shared access to any interactions* with project data and documents views. To describe these interactions by their impact and complexity regarding updates of project information, we propose to distinguish the following interaction levels:

- **visualization** (*project documents are only reviewed but with additional information level*),
- **annotation** (*project documents are not modified but has an additional level of information with annotations*),
- **modification** (*direct interaction with project documents and direct modifications or adjustments*).

The proposed types may be regarded as following the logics of BIM software classes of viewers, checkers, and molders. Also, in addition to the proposed types, and with the following focus of this work on touch interactions with project documents the touch gestures should be outlined as well “*move,*” “*pinch,*” “*zoom,*” “*drag,*” “*click*” or “*double click.*”

To ensure the project quality and management optimization, and to avoid data losses or misinterpretations, the digital interactive and collaborative tools should be the mediators at project meetings. They would provide a clear visualization and facilitation of interactions with the project information. In addition, these interactive mediators for decision support should be a part of the technical core and complete a digital continuity of project development.

2.2.2.3 Technical: BIM/4D and Lean planning use for collaboration

Need for relevant visualization and interactions for 4D collective use at the meetings

From the technology perspective, a digital solution for mediation of BIM/4D-based efficient collaboration during the meetings should provide ***a quality visualization, data continuity and easy access to the project information*** which allow to foster project understanding and participation at decision-making by all project team members.

BIM enables the development of the virtual nD models of the project, encompassing all kinds of data. 4D BIM allies the virtual 3D model of the construction project with the construction schedule, and it occurs mostly at the pre-construction phase of project development. On this level the work is collaborative and appends new information about processes to model data, and also it offers a path for other nD BIM simulations (maintenance needs, acoustics, processes, costs, energy requirements, sustainability, accessibility and life cycle analytics) (Halin et al., 2012).

Due to the ***complexity of information types and different user backgrounds, and different collaboration aims***, efficient 4D ***visualization and efficient user interactions*** are not easy to provide. Fischer et al. summarize that: “*Visualization is successful if the entire team and all relevant stakeholders have the same understanding of what is being built and how it is being built*” (Fischer et al., 2017; Ch.12). There is a ***strategic value to a good quality visualization*** which mediates the information and activities at the meetings and fosters more efficient decision-making (Whyte et al., 2008).

The ***need for adapted and shared views*** occurs during collaboration. The configuration (setting) of a synchronous collaboration environment adapted to BIM should provide project team members with the relevant view of a model for each project discipline (domain models) and interactions with it (Isikdag and Underwood, 2010). Yet, The 4D tools are mostly limited to a ***single window without customization to user profiles*** (Singh et al., 2011). Thus, further implementation of ***domain-specific, intelligent filters*** to facilitate users’ selection and interpretation interactions during the work with BIM model viewers and ***shared filters*** to improve the understanding between disciplines (Lee and Jeong, 2012). The 4D visualization assists with ***various perspectives presentation*** to the project team members, not necessary seeing the project in the same way (Fischer et al., 2017; Ch.7).

The clarity of visualization is essential for the efficient use of 4D for decision-making. The information overload may have negative impacts on project understanding and collaboration efficiency, therefore the visualized information and *model development level must correlate with the decision-making objectives*. In addition, *an adjustable level-of-detail* relevant to different disciplines and users must be integrated into future 4D simulation solutions (Porkka and Kähkönen, 2007). “*Collaboration requires knowing what signals the other party is sending, that is, whether a provocation has actually occurred or whether they intend to collaborate. Thus, clarity and transparency are essential.*” (Fischer et al., 2017; Ch.13).

The visualization of *4D models has some specific features related* to the needs to easily identify the elements of the model which correspond to construction task types (construction, demolition, temporary, etc.) and to the timeline (done, ongoing, to be done), task status (ready to launch, paused, etc.) or allocation to a particular construction team. As outline Fischer et al. the efficient 4D simulation “*...accurately predicts building and team behavior and leads to optimization of project solutions.*” (Fischer et al., 2017; Ch.12). Therefore, the development of efficient 4D visualization may be challenging. Various studies proposed a number of approaches to the issue, by proposing optimization of color scheme on 4D models (Chang et al., 2009), task status (Sacks et al., 2011), or development of a system of signs to visualize construction risks (Hartmann and Vosseveld, 2013).

Easiness of user interactions and *flexibility of information visualization* mediate collaborative development of project knowledge, and influence the collective decision-making (Dossick and Neff, 2011). From a perspective of interaction quality, BIM tools support well project documentation design and problem discovery, but do not fully support the dynamic activities essential to decision-making. 4D BIM uses may be beneficial to collective decision-making at the meetings. User-centered design has proven to be beneficial for development of a socio-technical solution designated for 4D collective use. (Zhou et al., 2014). These complex requirements for visualization are fostering the use of novel and more interactive approaches.

Need for relevant tools for collaboration 4D and Lean planning

Several studies had an opportunity to investigate the joint implementation of BIM and Lean. They establish a basis with the comprehensive feedback on 4D and Lean principles use. The studies emphasize the implementation benefits and mostly focus on production management mediation. They emphasize the requirements for future digital systems to support the mediation.

From the BIM perspective, the 4D visualization use for decision support requires the development of new efficient, and 4D adapted means *for tracking and reporting on meeting decisions* (Porkka and Kähkönen, 2007), as well of the means to support *continuous updates of a 4D* model in order to provide the relevant information for decision-making (Fischer et al., 2017; Ch.12). The 4D modeling is inevitably *dependent on planning activities*, and may benefit from collective inputs from different project team members (Malsane et al., 2015). Moreover, in addition to the professionals input, the effective scheduling tools may *recommend schedule optimization and alternatives* options (Bourne and Weaver, 2018), and propose allow the use of *automation tools for monitoring* construction (Ratajczak et al., 2019).

And from the Lean perspective, most of the construction site management lacks tools with a *user-friendly information visualization*, as well as the tracking, learning and connection to relevant sources of information. The visualization of information is important to avoid construction errors and schedule

deviations. Thus, synergy of BIM and Lean and joint implementation with assistance of a digital tool enabling an integrated approach would address these issues.

The integrated approaches consider the implementation of collaborative project planning systems like LPS® enabling pull planning. Such systems should include: *a milestone schedule, phase schedule, lookahead schedule, weekly work plans; which would be created in a collaborative way.* The proposed levels not only beneficial from the project and construction management perspectives, but also form the interface design and use scenarios perspective.

The schedule levels define visualization and the interactions for the 4D-based collaboration solution and its use scenarios, which describe the collaboration situation – the project meeting goals, participants, project phase, etc. Also, the system must enable features for reliability and learning must be enhanced by the interface as well. To enhance the visualization quality and interactions, the use of *an interactive digital dashboard for construction planning visualization, adjustments and progress may be beneficial.*

Key points of 2.2.2

Emphasis of the requirements for 4D-based collaboration tool and user interactions

The requirements for the tools evolve together with the evolution of the AEC approaches to design, implementing BIM, to project management with the integrated and collaborative project delivery methods like IPD, and to construction management with Lean construction. Thus, a variety of social and technological factors shape the requirements.

Moreover, the digital technologies evolve as well, allowing for more advanced efficient technological solutions such as web-based applications, cloud data-management, high resolution touchscreens, to be considered for the mediation of the AEC collaboration. Thus, together with the already identified by previous studies and the emerging requirements for 4D-based collaboration tool, there is firm basis for the design and development guidelines.

In our approach the requirements are categorized in three levels, corresponding to the global “social” context of the digital collaboration, to the activity related level encompassing the actors (users) interactions and use of the mediators, thus encompassing “social and technical,” the lowest “technical” level focuses on the specifications for visualization and interaction for 4D and Lean collective use:

- Social: transformation of processes, organization and roles:
Need for practices and approaches relevant to the digital and integrated practices;
Need for digital data continuity, accessibility and interoperability;
- Technical and social: digital collaboration environment setting:
Need to enhance BIM and digital supports use for collective decision-making
Need to enhance interactivity, communication and mediators for collective use;
- Technical: BIM/4D and Lean planning use for collaboration:
Need for relevant visualization and interactions for 4D collective use at the meetings;
Need for relevant for collaboration 4D and Lean planning.

Summary of the Chapter 2

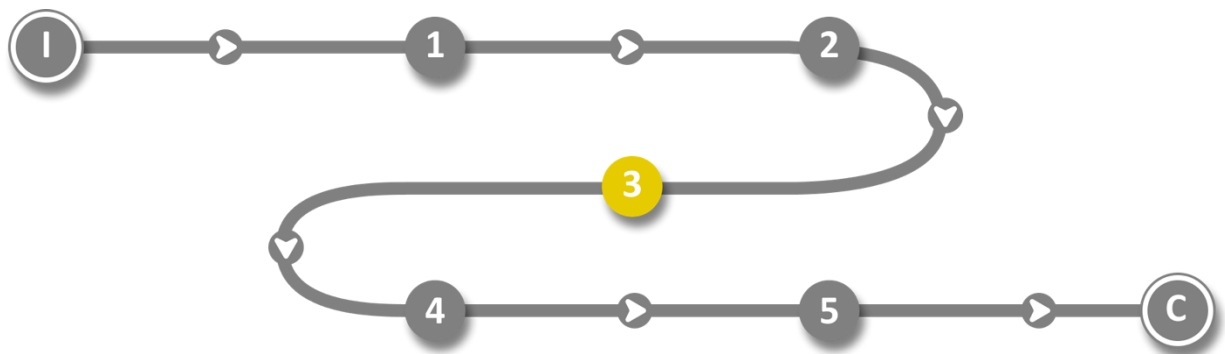
Research method and identification of requirements for 4D-based collaboration

- This research investigation considers the technology, people and processes dimensions of BIM, Lean construction and Integrated project delivery implementation. This research converges with the domain of HCI and UCD approach. The aim is to improve the collaboration quality for AEC professionals, who would benefit from the development of efficient tools, protocols and processes, with the study context of 4D BIM and Lean collaborative use at the project team meetings.
- The research proposes a digital approach to collaboration, encompassing STS theory to describe the macro level of the technical and the social aspects of the BIM-based collaboration and more integrated work context; the use of AT on the mezzo level to model collaboration session interactions between the actors – project team members, the mediators – digital tools, like touch tables and collaborative software with natural user interface, and the objectives – collaboration goals in the context of their work community; and on the micro level the User-centered Design and Design thinking provide the tools and methods for design and development of useful digital tools and collaboration scenarios.
- The commercial and research issued solutions 4D BIM and Lean developed to answer the demands from the industry to achieve interoperability, enable modeling, planning, clash detection, construction production management. However, their design and core features do not always enable the efficient implementation of 4D BIM uses, data integration, nor provide interfaces for interactive and collective decision-making (B1-3). The requirements for the tools evolve together with the evolution of the AEC approaches. This chapter concludes with the Emphasis of the requirements for 4D-based collaboration tool and user interactions.

Chapter 3.

Experimenting with BIM/4D and NUI use for synchronous collaboration and decision-making

The current chapter continues the investigation, and it presents the results of digital synchronous co-located collaboration experiments with an aim to identify requirements for improved collaboration, BIM/4D use, collective planning and natural interface interactions. First, it emphasizes the outcomes of a 3D and 4D based synchronous collaboration experiment “Digital Synchronous Collaboration with touch-tools” with students during their work on a construction project in groups (3.1).



3.1 Digital synchronous collaboration: a pedagogical experiment

This section emphasizes observations from a digital synchronous co-located collaboration pedagogical experiment (the experiment) investigating synchronous collective decision-making by multidisciplinary student teams via digital AEC project documents on a digital collaboration table (DCT). The observations were made during the weekly student's project review with the pedagogical team i.e., Digital collaboration sessions. First we outline the experiment context, next we present the research method and mixed data gathering tools allowing to study the macro level encompassing digital collaboration (3.1.1), the mezzo level focusing on digitally mediated activities during the meetings, and the micro level investigating the digital project documents, 3D/4D models use as the collaboration mediums (3.1.2), and concludes with feedback analysis summary (3.1.3).

3.1.1 Experiment context, setting and participants

3.1.1.1 Experiment description

Experiment focus

Together, all the participants were the users of a digital collaboration table (DCT) as the digital collaboration environment. The core research strategy was action research, however experimental strategy was supplemented throughout. For the sake of discussion, we refer to this research activity as the "experiment." The DCT was used at the meetings (collaboration sessions) as the mediator allowing digital project documents visualization and natural user interactions (NUI): a multi-touch table with the collaboration software "Shariing"⁴⁵ by Immersion⁴⁶. Such a tool offers:

- *a homogenous interface for all types of project documents (such as 2D plans and tables, 3D or 4D models) to avoid switching between dedicated visualization software;*
- *easily accessible interactions and ease of learning for all collaboration participants;*

The experiment provided us with a unique context for the observations of collaboration, and for the use of digital project documents, 3D and 4D model studies. The experiment allowed to:

- *survey the user-perceived utility of a digital tool with natural user interactions;*
- *collect suggestions for improvements of the digital medium, to collaboration scenarios and to the digital project documents use;*
- *study digital collective decision-making activity and interactions.*

For the research, both individual and group perceptions were important. The results contribute to the development and design requirements of a novel collaborative decision-making tool.

Experiment phases

The experiment duration was 3 years. It started in 2018 with Phase 1, then continued with Phase 2 in 2018-2019, and concluded by Phase 3 in 2019-2020 (Table 13). Phase 1 of the experiment was conducted during the "Timber Challenge"⁴⁷ pedagogical design and construction exercise in 2018. Where Step 1 was the Timber Challenge, design and construction phases, Step 2 was the collection of the users' feedback and the adjustments to the collaboration sessions. Phase 1's feedback showed the utility of DCT and suggested improvements for the next phase (Figure 64).

The further Phase 2 had two parts. At Phase 2.1, as at Step 1, the students were introduced to the work with the DCT during the first semester for the “Collaborative design project” exercise. The DCT introduction aimed to train all students to be efficient with the digital collaboration tool during the upcoming Timber Challenge. The next Phase 2.2 started with Step 1 - the Timber Challenge 2019 design phase and feedback collection. It concludes with Step 2 Timber Challenge 2019 construction and the new adjustments. The final Phase 3 also had 2 parts, and was strongly based on Phase 2, and it concluded the experiment.

Table 13 Summary of the experiments by type and phase

| Type | Subject | Phase | Collaboration context | Users | Year |
|-------------|------------------------------|-------|--|-------|------|
| Pedagogical | 2D/3D/4D collaboration study | 1 | Timber challenge design and construction | 9 | 2018 |
| | | 2.1 | Collaborative design project | 29 | 2018 |
| | | 2.2 | Timber challenge design and construction | 29 | 2019 |
| | | 3.1 | Collaborative design project | 36 | 2019 |
| | | 3.2 | Timber challenge design and construction | 34 | 2020 |

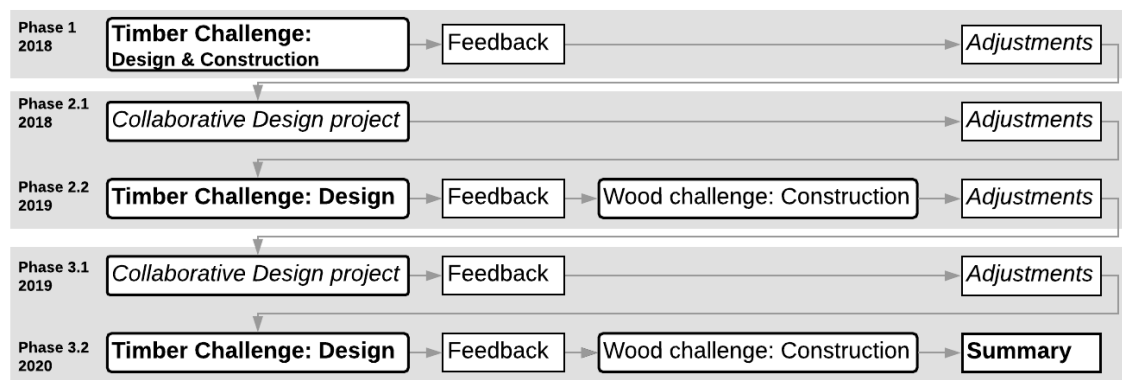


Figure 64 Schema of the pedagogical experiment phases and steps

Pedagogical context and projects

The “Architecture, Timber, Construction”⁴⁸ postgraduate program curriculum at ENSTIB⁴⁹ (Engineering School of Timber Technologies and Industry) offered us the context for the pedagogical experiment. The program receives about 30 students from architecture and engineering backgrounds every year. The focus of the program is on wood and timber construction studies. Since the postgraduate program unites students with three different backgrounds (architecture, timber engineering, civil engineering), the program gives students *an opportunity to collaborate with their fellow professionals from other disciplines*, to learn their vocabulary and workflows, to give to the architects a better understanding of engineering and engineers’ workflows and vice versa.

The curriculum is extended on two semesters. The first semester offers the curriculum’s main classes and a *Collaborative design project* in the core. During the second semester students leave for an internship and participate at the *Timber Challenge*.

During the first semester 6 teams of 5 students worked on a Collaborative design project. Every year the project subject changes, however it usually offers a mixed program for a public building combined

with housing. The pedagogical team brings a realistic scale to the project design by establishing a partnership with local authorities or associations. **Thus, they represent the “client” and describe their needs.** They also participate at project semi-final and final presentations and give consulting feedback on the project. Such a partnership gives students a better understanding of an importance of dialoguing with a client.

Students have a dozen weeks to develop a concept, create a 3D model, study a structure and building systems, and make a basic summary of costs and of ecological impact. Thus, they develop a complex project documentation and have a possibility to work on project details. Naturally, the main scope of the project design is the use and valorization of wood.

In addition, weekly project review meetings by the team with professors allow to follow up the project design development and to advice the students on architecture and engineering aspects of the project. For many students, the project is challenging due to the need to collaborate in a multidisciplinary team while basically discovering new workflows and to produce a quality project.

Presented aspects of this pedagogical exercise also shape a favorable context for our observations of the collective decision-making with the DCT.

Every year, the “Architecture, Timber, Construction”⁵⁰ postgraduate program launches a design and construction exercise of a project-based learning called “**Timber Challenge**”⁵¹. The challenge’s main tasks are first to design and then build, in teams, a small project with a wooden structure. Such an **exercise gives a realistic scale to the projects.** It strongly encourages students to foresee and avoid problems related to their design choices, and pushes students to anticipate construction solutions adapted to their designs and curriculum related skills.

In addition to the realistic scale, the students work in multidisciplinary teams of five, comprising of an architect, a timber structural engineer and a civil engineer (or other engineer), who are present permanently in person during the design and construction on campus. Also, every team has two additional members: a timber construction professional, for example a carpenter, and an international exchange student in architecture or engineering. These two members are introduced at the design phase, but come to campus in person mainly for the construction. Such a diversity of backgrounds emphasizes to the students an importance of efficient team communication and collaboration.

Every year, all the student teams work on a defined project type. They also share the same deadline and technical requirements (quantity of materials, structural elements, tools, etc.). The design and pre-construction preparations take 6-7 weeks in the beginning of the winter semester. The projects are assembled on campus by students during a week in Spring dedicated to the construction.

The small project with a timber structure must not exceed a surface of 15m² and a height of 3.8m, and have no more than 10 disassembled modules or elements. These requirements will further ease it to fit into a truck for transportation for campus to the project installation site, and Figure 65 Timber Challenge 2018 project “Ramificarré” built by student team H

Figure 65 illustrate examples of the built projects.

Such a short construction time and competition among teams for the best project, fosters students to put an effort on construction organization, and to continuously seek an **optimization for the project design for an easier assemble.** Thus, students remain very attentive during weekly project review sessions, have a strong motivation to express themselves and imply their skills. These aspects of the pedagogical exercise created a favorable context for our observations of the collective decision-making with the digital collaboration table during the Timber Challenge design phase.



Figure 65 Timber Challenge 2018 project "Ramificarré" built by student team H



Figure 66 Timber Challenge 2019 project "Bois Feuille Ciseaux" built by student team J

Project subjects by year

For the Phase 1 Timber Challenge in 2018 the design and construction subject were "Linea camera" which is a *contemplation and exhibition pavilion*⁵² for the botanical garden in Nancy, France. At the Phase 2.2, in 2019, the subject was the "Natural project" organic dump station⁵³ with some extensions, like a donation box, sitting bench or chicken housing. At Phase 3.2, in 2020, the students were building a "Bivouac durable" basic vacation cabin for primary and secondary school students coming on an educational school trip to a natural reserve.

For the Collaborative design project in 2018 the subject was an Eco-city bloc with a student residence a principal binding and some housing and a nursery in addition located in Epinal, France. The next year the subject was a *nature leisure reception and accommodation center* for primary and secondary school students in a natural reservation in Vosges, France.

The total amount of time for project design depended on the exercise: 6 weeks for a Timber Challenge, 12 weeks for a Collaborative design project. The Table 14 summarizes details about the projects by phase.

Table 14 Summary of the project subjects by phase

| Year | Phase | Pedagogical exercise | Project subject | Project surface | Design weeks | Construction weeks |
|------|-----------|----------------------|--|-----------------|--------------|--------------------|
| 2018 | Phase 1 | Timber Challenge | “Linea camera” botanical garden pavilion | ≈ 15 m2 | 6 | 1 |
| | Phase 2.1 | Design Project | Student residence, housing and a nursery | ≈ 500 m2 | 12 | n/a |
| 2019 | Phase 2.2 | Timber Challenge | “Natural project” organic dump station | ≈ 15 m2 | 6 | 1 |
| | Phase 3.1 | Design Project | Leisure and accommodation center | ≈ 300 m2 | 12 | n/a |
| 2020 | Phase 3.2 | Timber Challenge | Bivouac durable” basic vacation cabin | ≈ 15 m2 | 6 | 1 (canceled) |

3.1.1.2 Digital Collaboration sessions outline

Digital collaboration sessions summary

The digital collaboration sessions (DCS) were dedicated to the students’ project design and construction preparations review, and to pedagogical advising at the weekly meetings. After the first implementation of the digital collaboration table for the Timber Challenge at Phase 1 in 2018, the students and professors *suggested to introduce the table and digital collaboration methods to the students during their Design project exercise in the first semester*, prior to their Timber challenge in the second semester. This would make the students familiar with the approach while they are working on the design project, and before they start design and construction of Timber Challenge. In this way, the teams would take time to get experience with the digital collaboration table and become more confident users. Therefore, together with the feedback on the table improvements for AEC needs, it was introduced at Phase 2.1 for the Design project. The analysis should consider the differences of the pedagogical exercises, since they have a different number of participants, goals and project phases.

At Phase 1, during the Timber Challenge there were three sessions, at Phase 2.2 four sessions, at Phase 3.2 only two since the amount depended strongly on the design progress and team choices to spend more time on prototyping their timber structures. Not all student teams were participating at DCS at Phase 1 during the Timber Challenge 2018, but only two confident and curious teams who were the most interested in innovation and technology. Further, all the teams had an obligation to use the digital collaboration table as a medium for their weekly project review with professors.

The student teams were multidisciplinary, either a team of 5 for the Design project, or of 3 design team members joined by 2 other members for construction for the Timber Challenge. An architect, a structure or thermal engineer, and a construction expert were representing the pedagogical participants of DCS (Table 15). The choice of the professors present at the meeting depended on the review purpose and on the project phase. The professors provided expertise and input, similar to the consulting roles, but they also conducted the role of the real client representatives as project managers assuring that the design solution corresponds to the client requirements.

Table 15 Summary of Digital collaboration sessions (DCS)

| Year | Phase | Pedagogical exercise | Number of sessions | Number of student teams | Participants per session | |
|------|-----------|----------------------|--------------------|-------------------------|--------------------------|------------|
| | | | | | students | professors |
| 2018 | Phase 1 | Timber Challenge | 3 | 2 | 3 | 2/3 |
| | Phase 2.1 | Design project | 4 | 5 | 5 | 2/3 |
| 2019 | Phase 2.2 | Timber Challenge | 4 | 10 | 3 | 2/3 |
| | Phase 3.1 | Design project | 9 | 6 | 5 | 2/3 |
| 2020 | Phase 3.2 | Timber Challenge | 2 | 10 | 3 | 2/3 |

Digital collaboration table description

Professors and students had their weekly project-review meetings around a digital collaboration table (DCT). The DCT’s configuration has evolved through the experiment due to software and technology improvements, and as an answer to the *user* (professors and students) needs. The

configuration evolution can be distinguished through the versions of DCT: V1, V2 and V3. Figure 67 illustrates the versions' implementation through the progress of the experiment.

The DCT's V1 and V2 main element is a multi-touch screen of 46" HD, infra-red touch recognition frame, which is embedded in a wooden table frame. The V3's multi-touch screen parameters brought ergonomic improvements through the bigger size and better resolution augmenting to 55" and 4K, as well as more responsive touch technology: capacitive projected. In addition, mounting the DCT within the frame allowed for new angle changes, thus the table could be turned and used vertically, for example (Table 16). Figure 68 illustrates the data synchronization process, contents and outputs.

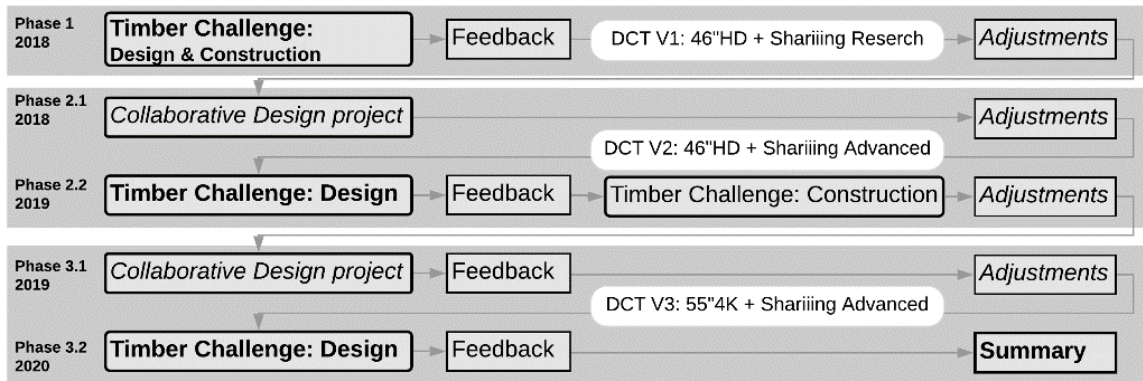


Figure 67 Schema of the digital collaboration table versions evolution through the experiment

Table 16 Summary of the digital collaboration table characteristics by experiment phase

| | Pedagogical exercise | DCT | Software version | Size and resolution | Touch technology | Frame | Screen positions |
|----------------|----------------------|-----|-------------------|---------------------|------------------|-------|-----------------------|
| Phase 1 2018 | Timber Challenge | V1 | Shariing Research | 46" HD | IR frame | Yes | Horizontal |
| Phase 2.1 2018 | Design Project | | | | | | |
| Phase 2.2 2019 | Timber Challenge | V2 | Shariing advanced | | | | |
| Phase 3.1 2019 | Design Project | | | | | | |
| Phase 3.2 2020 | Timber Challenge | V3 | | 55" 4K | PCT | No | Horizontal + Vertical |

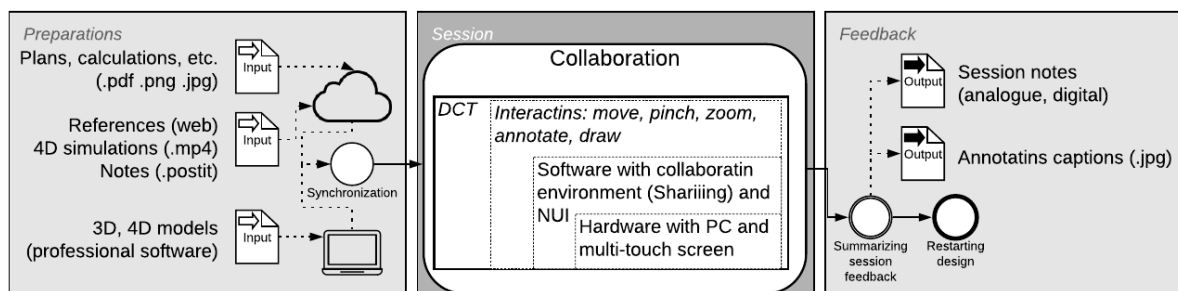


Figure 68 Synchronization illustration in the digital collaboration workflow

The touchscreen is connected to a computer (PC) running "Shariing"⁵⁴ software, a multiuser synchronous collaboration environment developed by "Immersion"⁵⁵. The use of the environment at project meetings allows users to:

- visualize project documents (plans, sections, 3D models, schedules, quantifications, etc.);
- share the same view even from different sides of the table;
- interact with the documents with touch gestures ("move," "pinch," "zoom," "drag," "click");

- *annotate documents temporarily or permanently;*
- *digital sketching.*

The software main versions were “Shariing Research” for V1, and were later updated to “Shariing Advanced”⁵⁶ alongside any future patches. The principle of use is the same for these versions, the Advanced version’s interface is more minimalist. It offers more fluid interactions with the documents and new sketch and annotation tools. In addition, Shariing Research visualizes 3D models itself (.obj and .IFC), and fluid interactions are possible, but it does not yet allow access to the model hierarchy.

Shariing Advanced 3D models’ visualization and interactions are managed by sharing an external screen with the table. Thus, when using Shariing Advanced, it is possible to share a view from a BIM viewer or design software (e.g., ArchiCAD, Cardworks, Navisworks, etc.) directly into the Shariing collaboration environment. Therefore, natural interactions and simple annotations are retained, and users still may manipulate the model with the external computer. In the current configuration, users may only save an annotation on a project document as a new 2D image (screenshot). Figure 69, Figure 70, Figure 71 illustrate the interface and general appearance of the three versions.

Population: digital collaboration sessions participants

During the exploratory Phase 1 only 9 users participated at DCS, where 3 users were the members of the pedagogical team and the other 6 were students of the “Architecture, Wood, Construction” program. At Phase 2 and 3 all the students were participating: 30 at Phase 2, 31 at the Phase 3. The professors were the constant members of the curriculum pedagogical team, so they were the same 5 users at Phases 2 and 3. Table 17 summarizes the number of participants, profiles and background, Figure 72 illustrates the summary.

Most of the students were already *active users of 3D modelling tools*, more than 60% of them were using the tools often or all the time. Almost a fifth of the total number of students were familiar with 4D before joining the curriculum. For example, at Phase 3 more than a quarter of students were familiar with 4D.

The curriculum curators trying to arrange an equal number of students with different backgrounds. Before joining the program, the students have usually followed an architecture, wood and timber engineering or civil engineering curriculums. However, sometimes students from other disciplines are accepted as well, such as general engineering, thermal engineering or forest studies. These students join the Civil engineering master’s program.

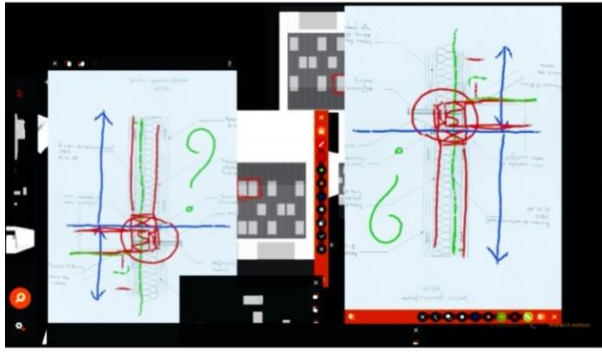


Figure 69 Digital Collaboration Table V1, left: interface; right: appearance

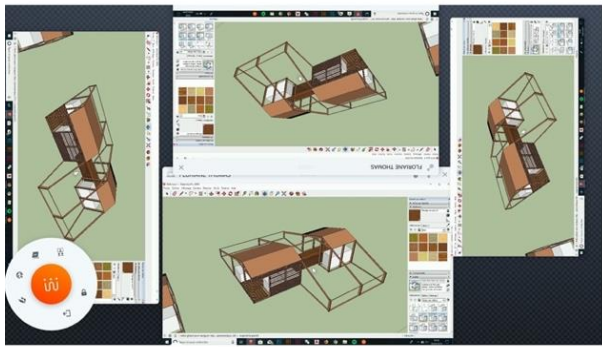


Figure 70 Digital Collaboration Table V2, left: interface; right: appearance

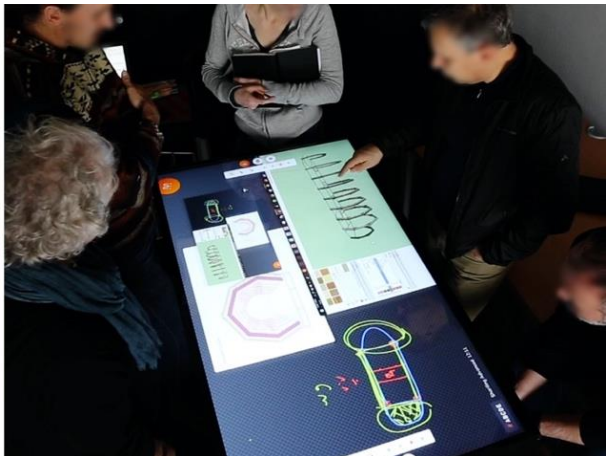
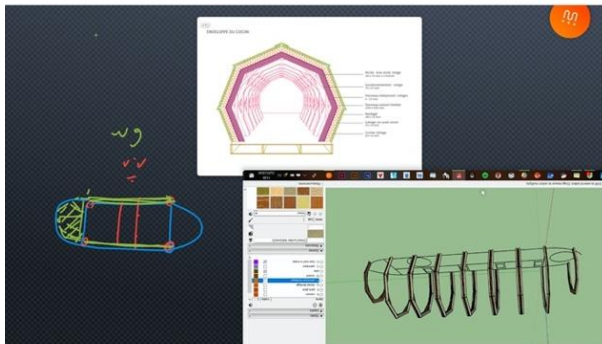


Figure 71 Digital Collaboration Table V3, left: interface; right: appearance

Table 17 Summary of Digital Collaboration Session (DCS) participants by the experiment phase

| Year | Phase | Pedagogical exercise | DCS Participants | | | Students profile | | | Students background | | |
|------|-----------|----------------------|------------------|------------|----------|------------------|-----------------------|------------------------|---------------------|-----------------|-------------------------------|
| | | | Total | Professors | Students | 3D active users | Initially 4D familiar | 2+ Years of experience | Architect | Timber engineer | Civil/Civil/a nother engineer |
| 2018 | Phase 1 | Timber Challenge | 9 | 3 | 6 | 6 | 0 | 1 | 4 | 2 | 0 |
| | Phase 2.1 | Design Project | 35 | 5 | 30 | 28 | 5 | 12 | 12 | 11 | 7 |
| 2019 | Phase 2.2 | Timber Challenge | 35 | 5 | 30 | 28 | 5 | 12 | 12 | 11 | 7 |
| | Phase 3.1 | Design Project | 36 | 5 | 31 | 29 | 8 | 10 | 12 | 8 | 11 |
| 2020 | Phase 3.2 | Timber Challenge | 34 | 3 | 31 | 29 | 8 | 10 | 12 | 8 | 11 |

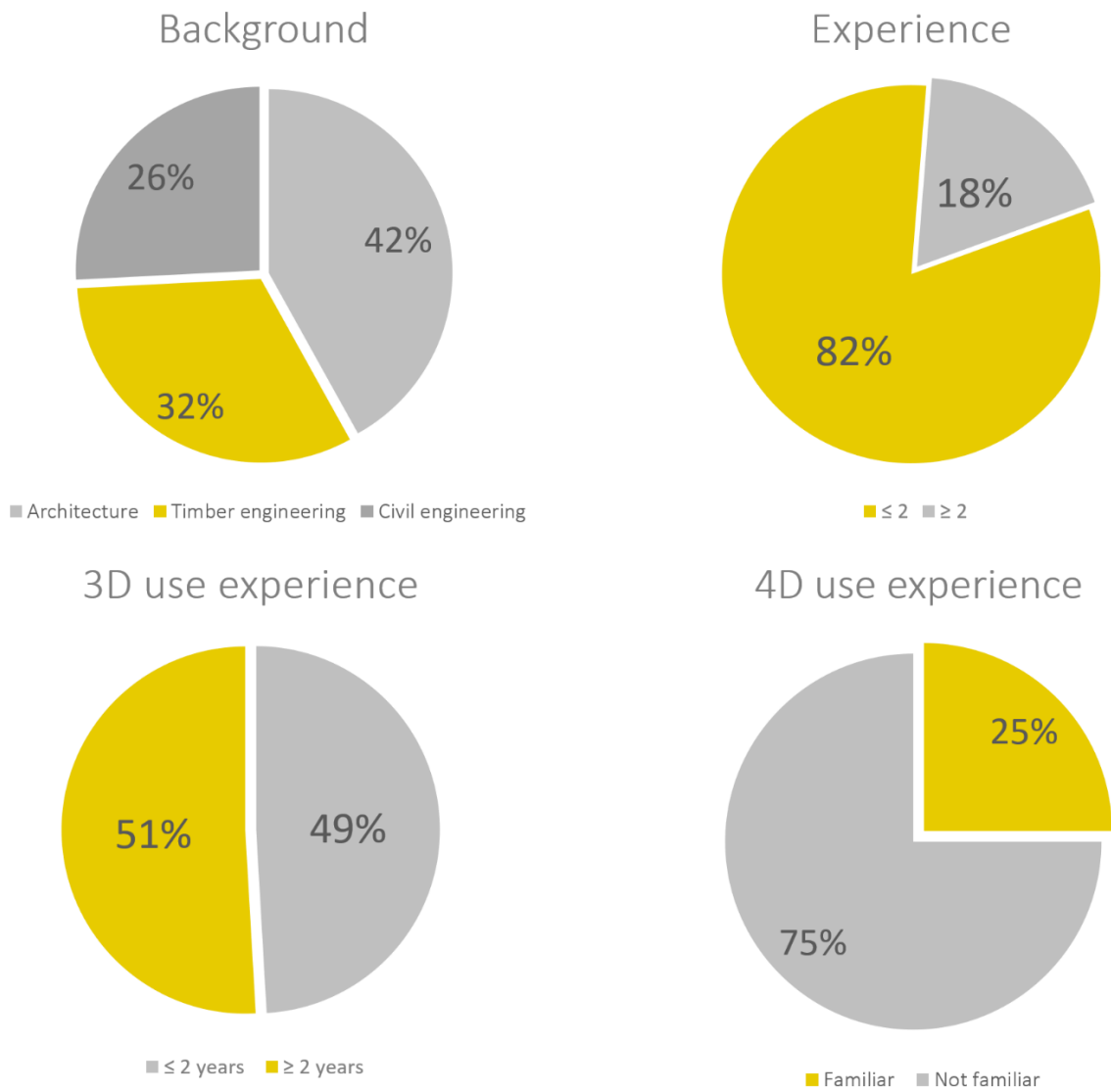


Figure 72 Summary of the user population

3.1.2 Research method

3.1.2.1 Experiment approach, scope and hypothesis

Experiment approach

The pedagogical experiment allows to continue the thesis investigation seeking to propose potential means to overcome the emphasized barriers: the limited use of BIM/4D for collective and collaborative decision-making (B1); and the need for efficient and more integrated collaboration with continuous digital data and workflows, mediated by relevant data visualization and interactions (B2).

The type and means for collaboration chosen by a project team would inevitably depend on the project type and on the project development phase. In addition, every phase of the project development have the specific tasks and purposes, thus shifts the focus of collaboration in correlation with the development needs. Hence, at the project review and planning meetings, the project teamwork and collaborative decision-making would adapt according to the meeting goal and consider the development phase, relevant documents and required group interactions. The experiments context allowed to observe such collaborative meetings through various project development stages.

The experiment study is structured with the previously outlined approach (2.1.1.1) encompassing:

- *the macro level socio-technical perspective on the digitally-based collaboration transforming the project processes, organization, interactions and context (Figure 73);*
- *the mezzo level providing activity perspective on the digital collaboration environment use as a mediator for the co-located synchronous collaboration for digitally based decision-making;*
- *the micro level evaluating the usability and requirements for the collective use of digital project documents for project review and planning.*

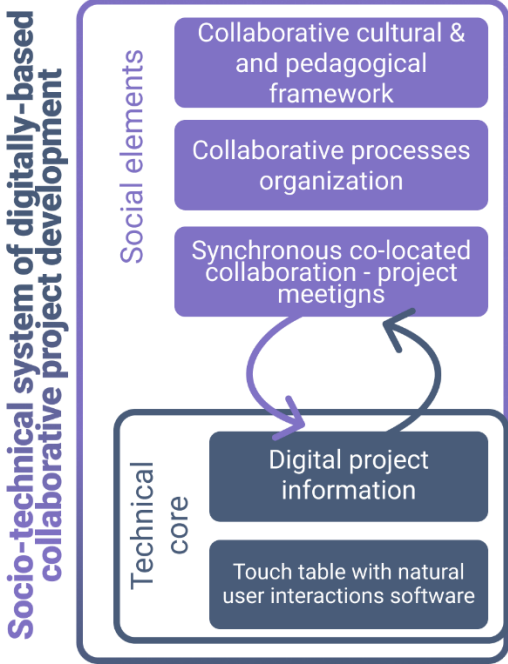


Figure 73 Schema of the socio-technical interactions of technical core and meetings social activity

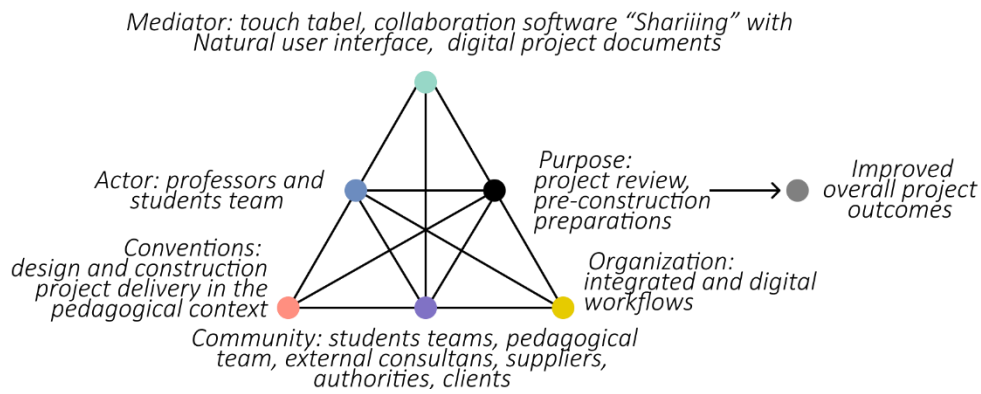


Figure 74 Schema of a collaborative project review by professors and a students team mediated by the digital tools

With the experiment design, we aim to continue investigation guided by the main research questions:

- RQ1. How does the shift of paradigm by the innovative approaches to project design, construction, and management influences the social and technical aspects of BIM-based collaboration of AEC professionals at the project review and planning meetings?
- RQ2. What is the influence of an implementation of a natural user interactions mediator^{xiii}, for collaboration of AEC professionals at the project review and planning meetings, their interactions and the project visualization quality?
- RQ3. What are the requirements for the multidisciplinary collaborative use of digital project documents and 4D BIM by AEC professionals at the project planning meetings?

In addition to our main research topics and aim, *the pedagogical potential from the use of digital project documents and interactive mediums*, and their influence on the educational processes was assessed as well.

Mixed research tools

A mixed method combining *qualitative and quantitative data collection* was implemented to gather a variety of data and to encompass different aspects of the digitally mediated collaboration at the project review meetings (see Figure 75), and to gather the results relevant to the social and technical levels of our investigation. The method includes, first, the observations and their video recordings of the meetings allowed to explore and analyze the macro level processes.

Second, the users' feedback was collected through a survey including such verified data gathering tools and custom questionnaire to collect information. The first part assessed the *team reflexivity* (Carter and West, 1998), and the third assessed how the participants perceive and use technology with the *Technology Acceptance Model 3* (TAM 3) (Venkatesh and Bala, 2008), in correlation with the mezzo level of our investigation.

The second part of the survey, allowing more detailed outline of the micro level, included the *System Usability Scale (SUS)* (Brooke, 1996) and was followed by *open-ended questions* allowing to collect more complex feedback on user experience and collaboration with the proposed digital collaboration table. This part of the survey is comparable to the questionnaire filled by the participants of experiments with AEC professionals prepared by the 4D Collab research team. Additional *questions on 3D, 4D and*

^{xiii} A touch table enabling collective synchronous interactions with collaboration software

planning complete this part of the questionnaire. The last part of the survey is focused on *4D BIM uses perception evaluation*.

Also, to complete the user profile, the experiment participants provided information about their background, years of experience, 3D and 4D experience, etc. *The semi-guided interviews with the teams* evaluating the perception of the digital collaboration table usability and collaboration requirements, specific to the AEC, complete the feedback.

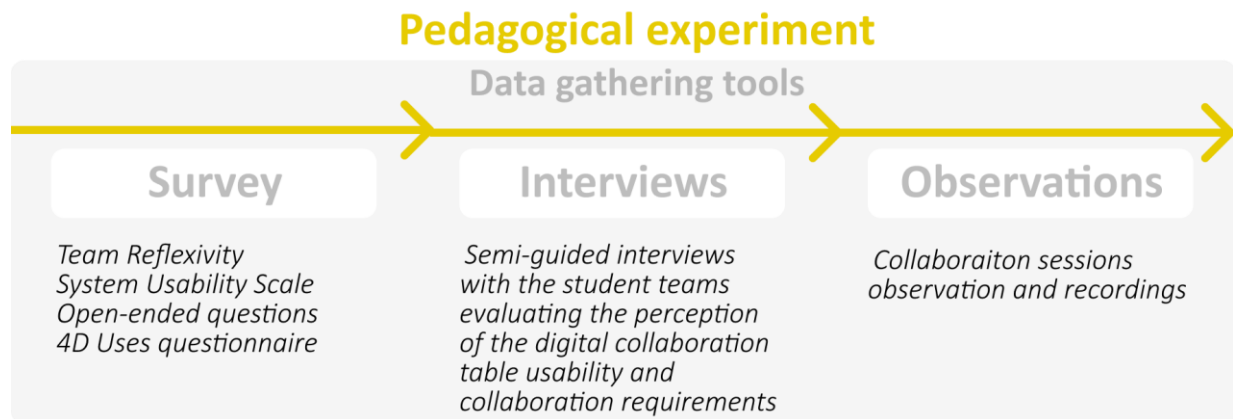


Figure 75 Schema of the user feedback and collaboration analysis tools

The summary of these explorations contributes to the study of usefulness and usability of the proposed digital collaboration setting, and to identification of collective use requirements for the future collaboration tool prototyping.

Experiment scope and hypothesis

One of the primary limitations of the study was related to the nature of the experiment context. The focus for the professors and the students was on the project design review and preparations for the construction, and not on the most effective use and evaluation of the proposed collaboration tools. Thus, the users did not necessary seek to explore all the features or establish an efficient digital workflow, but focused on the weekly meeting goals. However, such context represents a set of conditions representing ‘real’ requirements and issues, which differ from the controlled environment experiments.

Due to the limited use of BIM tools by the participants, the investigation scope was extended to the use of any digital project documents, such as 2D plans, sections, non-BIM 3D models, technical descriptions, etc., allowing to explore various needs for clear visualization and intuitive interactions, as well as relevant for decision-making information requests.

Such aspect as the integrated approach to collaboration was not specifically structured by any ‘contractual agreement,’ yet the multidisciplinary student teams were working within the pedagogical exercise setting, requiring equal participation of every student in the project development and fostering more collaborative and integrated team practices. The students shared ‘risks,’ ‘rewards’ and ‘objectives’ while working on their projects to receive their credits and to assure the maximum quality of the Timber challenge construction. Moreover, the use of digital tools and a ‘single source of information’ with a BIM model in the core of the project development was encouraged and implemented by most of the student teams.

Another limitation did not allow to study the use of Lean practices or Last Planner® System. Even though the students were familiar with some Lean construction (LC) concepts, and their brief experience with push and pull scheduling from the introduction to collaborative practices seminar, these practices did not occur during their collaborative work.

The project types were different from phase to phase; thus, their types may have influenced the work processes and collaboration of the students. In addition, some technical adjustments were made to provide the students and professors with the most relevant and interactive digital collaboration environment, therefore the evaluation of the tools must be considering such adjustments.

Despite the multidisciplinary background from the student’s population, the lack of experience from the real practices may impact the perception resumed in surveys and interviews, as well as their behavior during collaborative design, project meetings and construction at the Timber challenge.

However, the experiment context and setting allowed to gather data to evaluate the following thesis hypotheses:

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team.*
- *H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration.*

As well as, to consider several exploration hypotheses seeking to understand in depth the user’s profiles, team collaboration processes and collective and interactive use of the digital tools.

3.1.2.2 Data gathering tools

Team reflexivity, effectiveness and innovation

While studying group activities and team adaptation to changing environments and tasks, Michael West introduced the concept of “team reflexivity.” Reflexivity is described as: “*the extent to which group members overtly reflect upon the group’s objectives, strategies, and processes and adapt them to current or anticipated and endogenous or environmental circumstances*” (West, 1996). The team reflexivity is an important tool *for improvement of team effectiveness and performance* (Schippers et al., 2008; Schippers et al., 2015), moreover with a *higher reflexivity the team is more likely to have a better performance* (Carter and West, 1998), and *more efficient decision-making* (Schippers et al., 2014).

The effectiveness of team performance and work depends on many aspects, besides the efficient team would be able to accomplish the problem solving task (Kahai et al., 2004). West summarizes the elements of team efficiency (Table 18), where the team innovation and effectiveness are strongly related to the team reflexivity (West, 2012).

Table 18 Team efficiency components according to (West, 2012).

| Component | Description |
|-------------------------------|---|
| Task effectiveness | <i>ability of the team is successfully in achieve its task-related objectives</i> |
| Team innovation | <i>the extent to which the team develops and implements new and improved processes, products and procedures</i> |
| Team member well-being | <i>factors such as the well-being or mental health, growth and development of team members</i> |

Team viability *the likelihood that a team will continue to work together and function effectively*

Inter-team cooperation *the effectiveness of the team in collaborating with other teams in the organization with which it must work to deliver results*

Teams with *reflexive strategies also achieve better in innovation, focus on tasks and social functioning*. However, the reflexivity connection to team outcomes is not simple (Salas et al., 2017), and *a focus on innovation rather encourages an effectiveness than a reflexivity* (Carter and West, 1998). Also, studies show that, the team innovation is contingently influenced by their physical work environment (Schippers et al., 2015). Thus, in addition to the reflexivity, it is important to maintain the quality of the work environment. The use of the strategies of team reflexivity and innovation would be an effective response to high levels of work demands (Schippers et al., 2015).

The enhancement of reflexivity may be achieved by an adaptation of team’s management strategies and by fostering certain team’s qualities. For example, the reflexivity could be enhanced through a development of the *shared vision in the team or a transformational team leader behavior* (Schippers et al., 2008), which would influence the team performance as well. In addition, right skills and team roles, right team size and team clear objectives represent the necessary conditions for effective work, and foster reflexivity via aspects like:

- *Regular team reviews of the team’s objectives, as well as progress towards their fulfilment;*
- *Team member vigilance for external changes that could affect the team’s work;*
- *Awareness, review and discussion of the team’s functioning with a view to improving performance;*
- *Creativity, flexibility and adaptability; tolerance of uncertainty;*
- *Team members valuing the different perspectives, knowledge bases, skills and experience of team; members (West, 2012).*

In addition, the teams with these aspects reinforced would likely *see the challenges as opportunities* (West, 2012). *A clear team goal, psychological safety, team leadership coaching, and expertise diversity* would foster the reflexivity (Salas et al., 2017).

Furthermore, to enhance the team reflexivity, Shippers proposed a model (Table 19) of information-processing failures and remedies, such as: assuring useful, relevant and correct information; explicit information processing; explicit attention to the team’s decision-making process and potential disconfirming information (Schippers et al., 2014). For example, a creation of artificial milestones, time-outs and a norm of reflexivity would be the tools for fostering team reflexivity.

Table 19 A taxonomy of information-processing failures and remedies fostering team reflexivity proposed by Schippers (Schippers et al., 2014)

| Information-processing failures and areas of reflection | Examples | Remedies |
|--|---|---|
| Searching/ Sharing | <i>Failure to search for and share information</i> <ul style="list-style-type: none"> • Common knowledge effect • Hidden profile effect • Representational gaps • Motivated information sharing | <i>Assuring useful, relevant and correct information</i> <ul style="list-style-type: none"> • Giving the team more time to discuss • Access to informational records during discussion • Instructing team members not to form a priori judgments • Framing the task as a problem to be solved • Assigning roles associated with the information distribution • Having a norm to reflect |
| Elaboration/ Analyzing | <i>Failure to elaborate on and analyze information</i> <ul style="list-style-type: none"> • Framing • Heuristics • Positive illusions | <i>Explicit information processing</i> <ul style="list-style-type: none"> • Grounded in data • Offered as uncomfortable statements • Balance advocacy |
| Revising/ Updating | <i>Failure to revise and update conclusions</i> | <i>Explicit attention to the team’s decision-making process and potential disconfirming information</i> |

- Habitual routines
- Social entrainment
- Escalation of commitment
- Confirmation bias
- Interruptions
- Time-out
- Process accountability

To measure the team reflexivity Carter and West have *developed a reflexivity scale*, which contains 8 items on social reflexivity and 8 items on task reflexivity (Carter and West, 1998). The item questions are suggested to be rated on a scale from 1 to 7, however for the sake of homogeneity of our data we used the scale from 1 to 5 with further adjustments. The scale was validated and the link between team performance and reflexivity was confirmed as well by many studies. According to West there are three levels of task or social reflexivity:

- *high (47-56),*
- *medium (34-41),*
- *low (0-33) (West, 2012).*

For our study, the teams have filled the French version of the scale proposed by Facchin (Table 36, Appendix A), containing a subcategory of strategic reflexivity (Facchin et al., 2006).

On a *high level of reflexivity, the team is aware of the way it makes decisions* (Figure 19), and the team adapts to external and internal changes. On the medium level the team discusses and criticizes the work process and suggests alternatives. On a low level the team attention to task reflexivity or strategies is low. West also suggests *four types of teams and their outcomes by level of reflexivity*.

Table 20 Four types of teams and their outcomes by team reflexivity score according to West (West, 2012)

| High Task Reflexivity | |
|--|---|
| <i>Type D: Driven team</i> High short-term task effectiveness Poor team member well-being Short-term viability Moderate innovation High inter-team conflict | <i>Type A: Resilient team</i> High task effectiveness Good team member well-being Long-term viability High innovation High inter-team cooperation |
| Low Social Reflexivity | High Social Reflexivity |
| <i>Type C: Dysfunctional team</i> Poor task effectiveness Poor team member well-being Very low team viability Low innovation High inter-team conflict | <i>Type B: Complacent team</i> Poor task effectiveness Average team member well-being Short-term viability Low innovation Moderate inter-team conflict |
| Low task Reflexivity | |

System Usability Scale and Open-end questions

User feedback is essential to the UCD approach, therefore, the usability evaluation from the users is an important part of the design process. The emphasis of the usability concept was presented in section 2.1.2.2, yet to restate we study usability as *“the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use”* (ISO, 2018b). In addition, the usable system is *appropriate to its context, tasks, user’s profiles and needs* (Brooke, 2013).

The usability test may be focused either on usability problems identification and modifications, or on describing the usability using metrics (Sauro and Lewis, 2012). However, in addition to the usability

evaluation, user experience studies also *gather the user requirements and perspective* (Baxter et al., 2015). Additionally, usability testing allows to identify issues with the prototypes design during their development.

The implemented *System Usability Scale (SUS) is a free and quick tool* to measure the system usability, nevertheless it provides quite reliable results to measure the user’s precited usability and learnability (Sauro and Lewis, 2011; Brooke, 2013). In addition, the SUS is generally applicable regardless of evaluations of specific technology (Brooke, 2013), it has been widely used for various user experience evaluations. SUS is composed of ten traditional items to note on a five point Likert Scale (Brooke, 1996) that ranges from Strongly Disagree to Strongly Agree. The Table 34, presented in Appendix A, lists the scale items in English and French (Lallemand and Gronier, 2016a).

The result of the SUS is rated from 0 to 100, with the scores under 68 were not acceptable and *“acceptable” starting from 68*, since the score is interpreted not as a percentage but a percentile (Brooke, 2013). For example, the score of 68 would correspond to the percentile of 50, the 77 to 80, the 95 to 99,9 (Sauro and Lewis, 2012). The score interpretation summarized by Bangor et al. suggest the use of descriptive adjectives to provide a subjective label to the score’s number; where the score of 39 is correlated as “poor”, of 52 as “OK”, of 73 as “good”, of 85 as “excellent”, and the 100 as best imaginable (Figure 76) (Bangor et al., 2009).

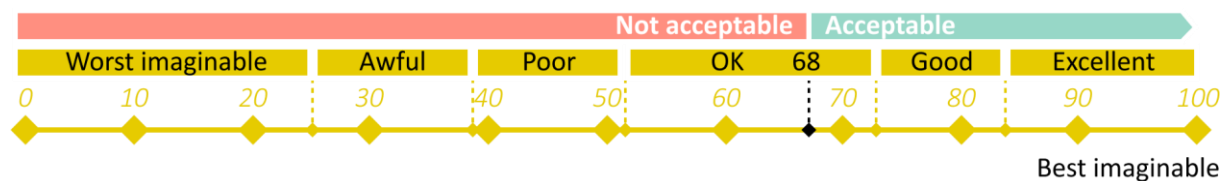


Figure 76 SUS score interpretation scale schema

In addition to this system usability score, the participants answered several *open-ended questions* (Table 35, Appendix A) about their experience with the use of DCT. The questions aimed to summarize the most positive and negative aspects of their experience from the use of the table, to gather *opinions about the use of 2D, 3D and 4D documents on the table, and to portray their perception off the decision-making process* improvements from the use of the table and of the 3D/4D.

4D BIM uses study

The use of BIM/4D and its perceived usefulness were also in the scope of the experiments. The participants widely use the 3D models, and they have already proven to be perceived as useful to a majority of AEC and BIM professionals. However, the use of 4D models and simulations stays limited. Therefore, it is important to understand if the students (sometimes already experienced AEC professionals) are already familiar with 4D, and how many of them are currently using it or choosing not to use 4D. Also, how do they perceive the use and potential of the emphasized 4D BIM uses (1.1.3.1). The survey was based on the survey about 4D BIM uses among the AEC professionals conducted previously by the 4D Collab project team^{xiv}, which aimed to identify the perceived usefulness of “4D BIM uses”. Based on the “4D BIM uses” proposed by (Guerriero et al., 2017), we offered a short survey to the participants of the pedagogical experiment. They were also asked, to evaluate the use of 4D for the following uses:

^{xiv} <https://www.4dcollab-project.eu/research/results>

- *scheduling,*
- *monitoring,*
- *site layout and environment management,*
- *safety management,*
- *clash detection,*
- *constructability management.*

The participants evaluated each 4D use on the five-point Likert chart. This study presented with exploratory, rather than conclusive results. However, it offers us with a better understanding of 4D uses perception by the young professionals.

Semi-guided interviews and observations

A series of semi-guided interviews with the teams was conducted at the end of the pedagogical exercises, to complete feedback on the digital collaboration experience and the use of 3D/4D on the DCT, as well as on their team collaboration experience. Every student team and the pedagogical team shared their team experience at a recorded interview. The group interview of the team was chosen over an individual interview to highlight the team collaboration experience and study their interactions as an Actor representing a collaboration persona.

All the teams from Phases 2.2, 3.1 and 3.2 provided their feedback. The interviews were mostly focused on the proposed topics for the guidance (*e.g., beginning of the session; basic interactions; place of the 2D,3D,4D; decision-making and session summary; difficulties, advice and proposals*). The team interviews duration did not exceed 20 minutes. The users showed and verbalized a high level of trust and openness towards the interviewer and expressed themselves relatively freely.

The *thematic analysis* method was used to emphasize the interviews. This qualitative research analysis method is flexible, relatively easy and provides insights, it allows to sort and identify themes or patterns (Braun and Clarke, 2006). The method proved to be useful in AEC and BIM studies (Vass and Gustavsson, 2017; Kassem et al., 2018; Sujan et al., 2019), but also in interface design, since it provides a better user understanding for the future user interactions design (Preece et al., 2015). In particular, through the thematic analysis, an interface designer acquires an identification of the interface problems (*dissatisfaction about an aspect of the interface; of confusion/uncertainty about an aspect of the interface; of confusion/surprise at the outcome of an action; etc.*) or of the content problems (Preece et al., 2015).

Moreover, the collaboration observations, allowed to better portray decision-making and main collaboration dynamics aspects, such as:

- *duration of the session,*
- *documents used for discussion,*
- *interaction gestures,*
- *and decision-making point.*

3.1.3 Analysis summary

3.1.3.1 Macro level of the digital collaboration summary

Digital collaboration sessions observations

The digital collaboration sessions (DCS) were dedicated to the students' project design and construction preparations review, and to pedagogical advising at the weekly meetings.

After the first implementation of the DCT for the Timber Challenge at Phase 1 in 2018, the students and professors suggested to introduce the table and digital collaboration methods to the students during their Design project exercise in the first semester, prior to their Timber challenge in the second semester. This would make the students familiar with the approach while they are working on the design project, and before they start design and construction of Timber Challenge. In this way, the teams would take time to get experience with the DCT and become more confident users.

Therefore, together with the feedback on the table improvements for AEC needs, it was introduced at the Phase 2.1 for the Design project. The analysis should consider the differences of the pedagogical exercises, since they have different number of participants, goals and project phases. However, half of the teams claimed that they did not feel fully confident about their use of the DCT, even after the first semester use for the Design project and the dynamic use of the table. The main reason, highlighted during the interviews was *stress and pressure* from the dynamic and complex work, and *need to collaborate with the other disciplines*. Yet, the teams with better reflexivity were producing better designs, therefore felt confident at the meetings and used the table for their benefit.

At Phase 1, during the Timber Challenge there were three sessions, at Phase 2.2 four sessions, at Phase 3.2 only two since the amount depended strongly on the design progress and team choices to spend more time on prototyping their timber structures. Not all student teams were participating at DCS at Phase 1 during the Timber Challenge 2018, but only two confident and curious teams who were the most interested in innovation and technology. Further, all the teams had the obligation to use the DCT as a medium for their weekly project review with professors.

The student teams were multidisciplinary, either a team of 5 for the Design project, or of 3 design team members joined by 2 other members for construction for the Timber Challenge. An architect, a structure or thermal studies engineer, and a construction expert were representing the pedagogical participants of DCS. The choice of the present at the meeting professors depended on the review purpose and on the project phase (Table 21). The professors provided professional expertise and input, similar to the consulting roles, but they also conducted the role of the real client representatives as project managers assuring that the design solution corresponds to the client requirements.

Table 21 Summary of Digital collaboration sessions (DCS)

| Year | Phase | Pedagogical exercise | Number of sessions | Number of student teams | Participants per session | |
|------|-----------|----------------------|--------------------|-------------------------|--------------------------|------------|
| | | | | | students | professors |
| 2018 | Phase 1 | Timber Challenge | 3 | 2 | 3 | 2/3 |
| | Phase 2.1 | Design project | 4 | 5 | 5 | 2/3 |
| 2019 | Phase 2.2 | Timber Challenge | 4 | 10 | 3 | 2/3 |
| | Phase 3.1 | Design project | 9 | 6 | 5 | 2/3 |
| 2020 | Phase 3.2 | Timber Challenge | 2 | 10 | 3 | 2/3 |

Further we describe the phases 2.2 and 3.2 representing the Timber challenge pedagogical exercise, since these phases allowed to gather the most relevant to our main study aim, providing the

multidisciplinary collaboration with digital tools context, encompassing design, pre-construction and construction phases, and focusing the meetings goals on preparations for the timber construction, thus providing high motivation and the “real project” issues.

Due to the specifics of the pedagogical context, the project review meetings time was limited to allow the professors to consult all the student teams. Yet the meeting duration often varied, and was extended if necessary. In general, the collaboration session duration was expected to be around 20 minutes, but in case of important issues they were extended, or shortened if the issues were quickly resolved. We do not compare the meetings from Phase 2.2 to 3.2, since the number of meetings was not the same. The two meetings of 3.2 correspond to the last two meetings of 2.2, which were concluding the architectural and structural design adjustments and pre-construction preparations including materials quantifications, fabrication and construction methods outline, optimization of the construction sequence (Figure 77).

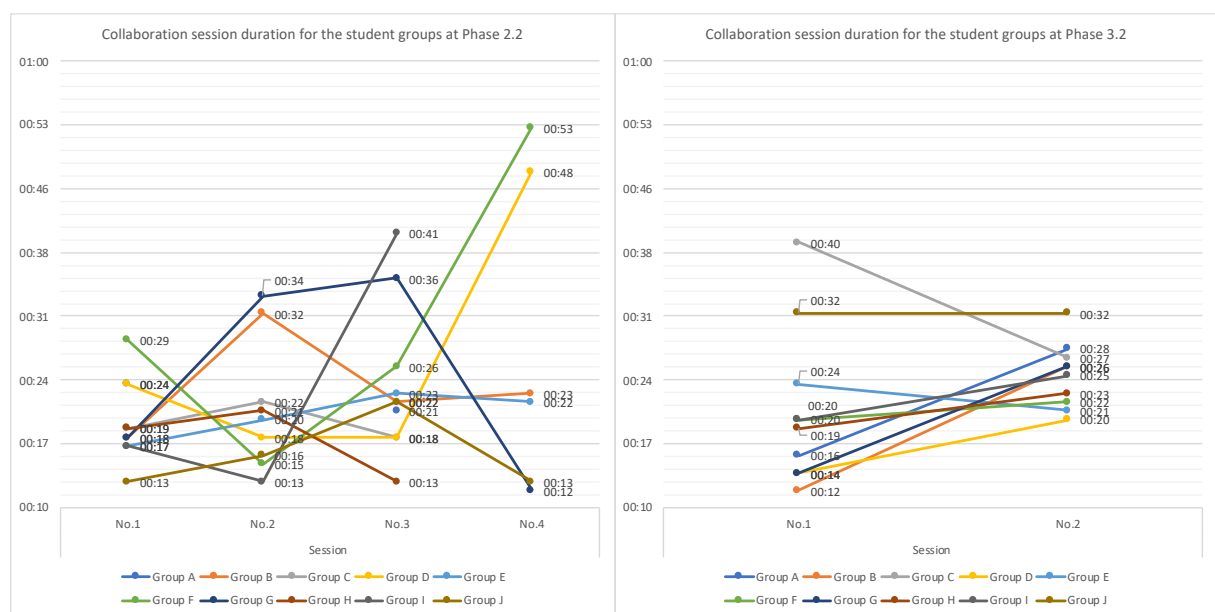


Figure 77 Summary of the collaboration session duration by the group and Timber challenge

Most of the meetings started with the 5-10 minutes presentation of the design advancements and issues by the “design team” students, followed by discussion, by decision-making related to design issues and construction issues.

Sometimes sessions concluded with *formal and collective outline of the design tasks* summary, but only for **30% of the meetings**. The students were taking individual *paper-based notes only for 40%* (mostly only one student in charge of the notes, except the difficult long meetings) of the meetings, and one professor was taking the paper-based notes at all the meetings.

Regarding the meeting reporting, 80% of the students consider the proposed configuration of the DCT as useful. Yet, the proposed tools and interactions must adapt for such uses. A student did not consider the proposed tools useful, since “... *the annotations and issues identified verbally are not better recorded than with a classic report in my opinion.*”

Regarding the interactions with the digital project documents, **at all the meetings at least 3 from 5-6 participants performed navigation interactions** such as “move, pivot, zoom” with the digital

documents on the DCT, allowing better visualization of the relevant project information. Another unique interaction such as *“full screen” visualization* of the view of the project on the touch display occurred at **60%** of the meetings. *Annotations of the digital documents and digital sketching* occurred slightly more often than “full screen” visualization, at **65%** of the meetings. The occurring interaction types do not seem to have significant impact on the meeting duration. The annotations and sketching occurred only when design and structure issues were identified. These observations are to be compared with the survey results and interviews feedback.

Regarding the interactivity, a student with engineering background notes that the use of the table *fostered more “democratic” interactions*, according to an architecture student (S86A): *“... it's practical because unlike someone who has a mouse in his hand, everyone can touch and express themselves.”*

Regarding the transformation of the collaboration practices, a timber engineering student (S19WDI) comments that the implementation of the proposed digital workflow and interactive table for the meetings: *“... requires a prior organization to produce, choose and gather the documents. This step is sometimes long, but rather useful. In my opinion, it is the most important part of the collective summary,”* and such suggestion is often repeated by other students. However, another student (S13T) with engineering background from the team which essentially used the 3D models as the discussion medium, comments that *such digital mediums use does does not augment the meeting preparation: “requires less preparation time since you can display the 3D model.”*

Regarding the skills required to use the table, *some students did not feel confident in their skills*, even after many sessions, but also many students did feel confident. An architecture student (S97A) emphasizes that the use of the digital collaboration table for the Design project *allowed “... more ease of use on the Timber Challenge;”* another student (S102T) highlights that it was *easy to start using the table;* and unlike with their professional software tools a civil engineering student (S32C) that it *allows all professors to participate in the project documents interactions.*

However, some interactions are not yet advanced enough. An architecture student (S12A) comments that he is *used to sketch at the meetings* to explain the ideas, and the digital tool precision did not allow the more ergonomic and detail sketching gestures than *paper and pen, thus disrupted the sketching habit.*

Among many future suggestions the students mentioned the *need to integrate more automated dataflow “an adapted file deposit platform so that we can each prepare the return and organize our documents on our own.”* (S31T). Moreover, such platform should also be a part of the data workflow as emphasized by many students, with an easy way of *“... automatic recording of annotations in the source file”* (S97A). Another often mentioned request, was the *need to automate preparations* and synchronization with: *“definition of the meeting goals and relevant to them documents”* (S23T). Thus, in summary all the activities related to the organization of the meetings are requested, as emphasized student S102T a request for automated: *“organization: key points to be addressed, management of all points with the contributions of solutions; summary; assignment of tasks.”*

Team reflexivity summary

The team reflexivity data from the Timber challenges was gathered from 8 teams in Phase 2.2 and from 10 teams in Phase 3.2, thus 18 teams in total, the other experiment phases were not analyzed. For all student teams except the team H at the Phase 2.2, the *task reflexivity was always lower than the social reflexivity*. Figure 78 summarizes the low (red zone), medium (yellow zone), and high (green zone) levels of reflexivity for all student teams by phase.

In Phase 2.2, 5 student teams (A, C, D, G, I) presented “low” task reflexivity, 3 teams (F, H, J) “medium”, and no team “high”. During this phase, the social reflexivity was “low” for 1 team (G), “medium” for 2 (H, J), and “high” for 5 (A, B, D, F, I). The 3 from the 8 teams (G, H, J) results illustrate the similar levels of reflexivity scores for task and social reflexivity. However, the teams (A, C, D, I) gave a high social reflexivity score and the low task reflexivity, also one team (F) gave the medium score on task reflexivity and the high on the social.

In phase 3.2, similarly, 5 student teams (B, C, E, H, I) presented “low” task reflexivity, and 4 teams (D, F, J) “medium”, and 1 of the teams (G) with “high”. The social reflexivity was “medium” for 3 teams and “high” for 7. The 5 teams (A, D, F, G, J) gave “medium” task reflexivity and “high” social reflexivity score (see Figure 78 **Error! Reference source not found.**). Correspondingly, other 3 teams (B, E, H) gave “low” task reflexivity and “medium” social reflexivity; 2 teams (C, I) gave a score “low” to task reflexivity and “high” to social reflexivity. Only one team (G) presented with “high” for both.

From all teams the team G in phase 2.2 gave the lowest of both scores, and the team G at the Phase 3.2 the highest. The scores allowed to identify team types according to West team reflexivity, with three teams representing a resilient team, one team being a driven team, eight and the most teams seeming to be complacent teams, and five teams’ parameters suggest that they correspond to the dysfunctional team type (Table 22).

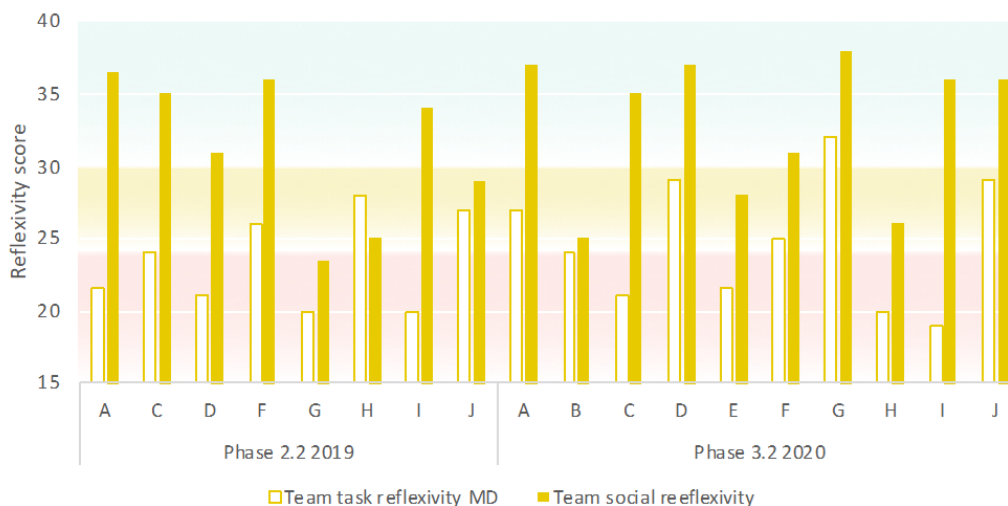


Figure 78 Summary of task and social reflexivity scores by experiment phase and student team

Table 22 Teams reflexivity and types according to (West, 2012)

| Reflexivity category 1 | Reflexivity category 2 | Team type | Phase 2.2 | Phase 3.2 |
|------------------------|-------------------------|--|------------------|------------|
| High Task Reflexivity | High Social Reflexivity | <i>Type A: Resilient team</i> High task effectiveness Good team member well-being Long-term viability High innovation High inter-team cooperation | - | G, D, J |
| | Low Social Reflexivity | <i>Type D: Driven team</i> High short-term task effectiveness Poor team member well-being Short-term viability Moderate innovation High inter-team conflict | - | - |
| Low task Reflexivity | High Social Reflexivity | <i>Type B: Complacent team</i> Poor task effectiveness Average team member well-being Short-term viability Low innovation Moderate inter-team conflict | A, C, D, I, J, F | C, I, F |
| | Low Social Reflexivity | <i>Type C: Dysfunctional team</i> Poor task effectiveness Poor team member well-being Very low team viability Low innovation High inter-team conflict | H, G | A, B, H, E |

Reflexivity scores from all the participants (as individuals), follow the group score patterns. From 51 users, 25 gave “low” (≤ 24), 20 “medium” (24-30), 5 “high” ($30 \geq$) task reflexivity score, and for the social reflexivity score 10 users gave “low”, 12 “medium” and 29 “high” scores.

Despite the small sample size, each team reflexivity scores were studied with linear regression analysis (Figure 79). The analysis indicates a potential dependence that the students team task reflexivity has *positive linear relationship* with the team social reflexivity (deviation from the horizontal is not significant, p -value=0,219, $Y=0.3916 \cdot X+22.7$), therefore the *teams with higher task reflexivity were likely to present the higher social reflexivity as well*.

Further, the reflexivity results were studied in relation with the provided System Usability Scores (SUS), suggesting as well *positive linear relationship between the team task reflexivity and team SUS* (deviation from the horizontal is not significant, p -value =0,153, $Y=0.7255 \cdot X+38,24$), suggesting that the higher task reflexivity would augment the system usability score, which is consistent with the “high and moderate innovation” characteristics of the resilient and driven teams. In addition, the analysis suggests *minor influence presenting the positive linear relationship of the team social reflexivity and the team SUS* (deviation from the horizontal is not significant, p -value =0,073, $Y=0.557 \cdot X+37.78$).

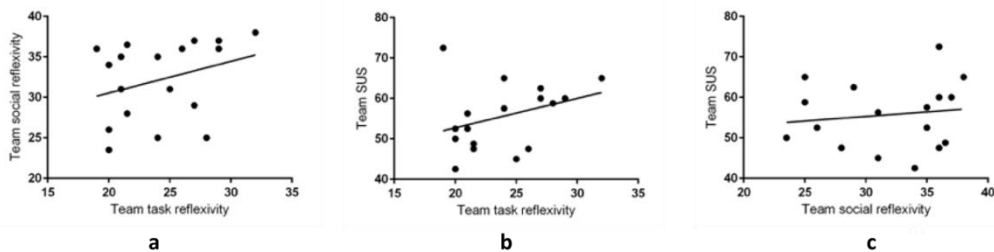


Figure 79 Linear regression analysis between: a. Team task reflexivity and team social reflexivity; b. team task reflexivity and team SUS; c. team social reflexivity and team SUS

The teams represent the activity actors in our study, however, with the individual participants data we were able to investigate in more detail the observed relationships (Figure 80). The analysis of the scores provided by each participant, *confirms the previously illustrated positive linear relationship between the task reflexivity and the social reflexivity* (deviation from the horizontal is significant, p-value=0,038, $Y=0.8391*X+34.44$). Moreover, the participants providing the *higher task reflexivity scores were likely to provide the higher SUS score* as well (deviation from the horizontal is significant, p-value =0,039, $Y=0.8391*X+34.44$). The study of relation of the social reflexivity and the SUS score from the individuals, is consistent with the teams' study, suggesting probability of the positive linear relationship, but with the deviation from the horizontal which is not significant and p-value=0,073, $Y=0.557*X+37.78$.

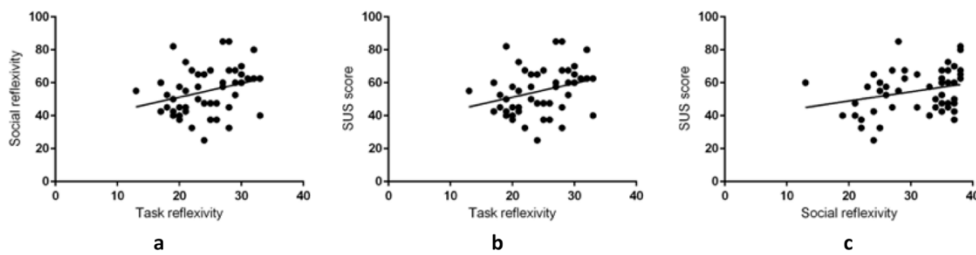


Figure 80 Linear regression analysis between: a. task reflexivity and social reflexivity; b. task reflexivity and SUS; c. social reflexivity and SUS

The distribution of Task reflexivity scores of those respondents who perceived that they *successfully achieved the tasks with the proposed system* (38 items, mean = 25.47) and the same distribution for those who found it to be a failure (13 items, mean = 21.38) were compared by two nonparametric tests, Kolmogorov-Smirnov (KS) and Mann-Whitney (MW). The KS statistic was 0.380567, p-value 0.083369; MW statistic 364.000000, p-value 0.011628. Therefore, we can claim that there is a minor difference in the scores, tending towards those who set a higher score to declare the system use a success, but this difference is not statistically significant.

Feedback from the different team types

The resilient team (G from the Phase 3.2) had high task and high social reflexivity; the session duration was not exceeding average. At the meetings, the participants were very calm, confident and did not perceive any “stressful” elements. The discussion was always very dynamic, and at least 4 from the 5-6 meeting participants were interacting with the digital project documents. The participants were visualizing and annotating the documents, as well as sketching and actively using the full screening visualization function (Figure 81).

During the interview, the team members reflected on the implemented work practices, and suggested the need to enhance their digital tools use. They also highlighted the importance of organization of the digital design process, and the required skills for the digital and collaborative design. The team also emphasized the importance of a “good mood and team spirit” which was essential for them and their work. Thus, they were capable to reflect on their social processes and the use of the technical tools in the core of the digitally based collaboration.

Regarding the system usability scale scores, the team members presented relatively high scores of 62,5; 65 and 80, which are suggesting, the fair or good usability of the proposed tool perception. During the first session the discussion was mediated by only 2D plan and section for another, and during the second session only with the 3D model of the project.

Regarding the collaboration organization the civil engineering student (S98C) commented, that: “... it would be useful to arrive [to the meeting] with the goals of the previous meeting, discuss the issues, and leave with the goals for the next meeting”. And reflected upon the meeting reports, that “... the screenshots were useful when we annotated the documents and drew details” according to the timber engineering student S96T.

Regarding the proposed digital collaboration environment, from the ergonomic perspective the team agreed on the need for the non-touch frame around the touch-display to put their notebooks and laptops on it. They also commented upon the use of the natural user interface and touch interactions, the architecture student S97A emphasized: “The touch gestures were improved, and all the interactions with the documents, including screen shots, were adapted and responsive. Thus, it was easier for us to interact with the documents,” and the student S98C suggests that in comparison with the Design project experience: “... we had less Random interactions”. The students also emphasized that in addition to visualization they relied on sketching during their meetings, according to S97A: “we also used the table for sketching with our fingers and it allowed us to discuss the design issues.”

And the main usefulness was in the 3D visualization quality and interactions, the student S98C reflects that: “It was mostly useful for 3D than other things. The professor often interacted with the 3D model of the project, and it allowed not to make the scale model.” Regarding the use of the digital documents and 3D models as mediums for collective decision-making, S96T states that: “... visualization was improved since we used only one 3D model, and only one PDF file as a single source of project information, and as the medium for this discussion.”

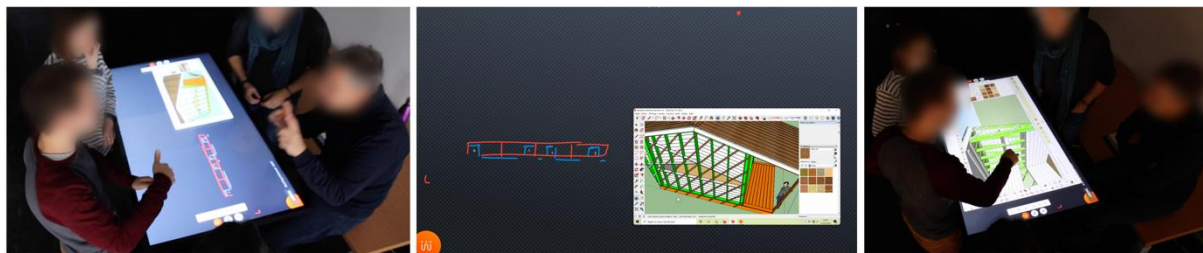


Figure 81 Collaboration session of the team G with the digital collaboration table, presenting Timber challenge project

The Complacent team (F from the Phase 3.2) had medium task and high social reflexivity; the session duration was rather average. At the meetings, the students were rather calm defending their idea of the project design, but not confident. They also perceived the sessions as stressful. The discussion was rather dynamic, ***focused mostly on the design issues solving***. At least 4 of the 5-6 meeting participants were interacting with the digital project documents, one student was permanently taking notes. The participants were visualizing, navigating and annotating the digital documents, as well as sketching and actively using the full screening visualization function (Figure 82).

During the interview, the students were glad to share their experience and opinions, and highlighted that they had a good perception of their social aspects of collaboration and interactions, with certain “*cohesion of the team.*”

Regarding the system usability scale scores, the team members gave low and coherent within the team scores of 40, 45 and 47,5 which are suggesting that they perceived the tool’s usability as “poor”. During the first session the discussion was mediated by a large variety of 2D documents, and during the second session the team mostly used the axonometry view of 3D model of the project.

Regarding the collaboration organization the timber engineering student (S93T) was glad to highlight that he oversaw the meeting preparations: “... I had my own small routine for the [table] use.”, and emphasizes that “we used only 3D and one pdf file, it was a good and efficient choice.” Regarding the meeting activities the architecture student (S95A) highlighted the need for a strategy of presentation and guidance of discussion, to stay focused on the goals: “You need to manage the meeting and not allow any divergences from the subject.” Moreover, regarding the collaboration skills, the civil engineering student (S94C) suggested to: “... use the table without professors, try it out and not be stressed by the Timber challenge.”

Regarding the proposed digital collaboration environment, the student S94C observed that: “We used the table less than in the first semester.” The student S95A emphasized the perception of the proposed digital tool from the design activities perspective: “... for me the table is the communication medium, to display our designs, but for the design it is not that important, it allowed mainly to discuss the project.” Yet, the same student recognizes that they used the table for discussion and recordings of annotations: “We made a lot of screenshots, but finally we mostly relied on our meeting notes, and not rely on the annotated documents.”

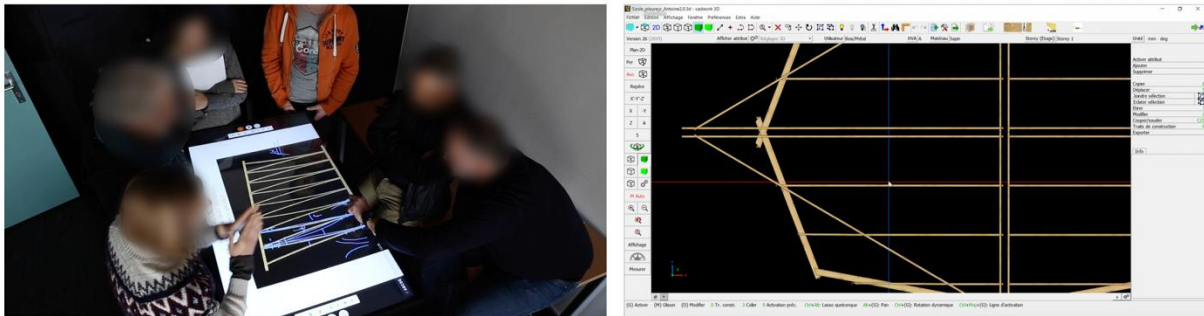


Figure 82 Collaboration session of the team F with the digital collaboration table, presenting Timber challenge project

The dysfunctional team (A from the Phase 3.2) had low task and low social reflexivity, the session duration was rather close to the average, as the other described teams.

At the meetings, the students were rather calm defending their idea of the project design, but not confident. They also perceived the sessions as stressful. The discussion was rather dynamic, **focused mostly on the design issues solving**. At least 3 of the 5-6 meeting participants were interacting with the digital project documents, yet without paper notes aside. During the first session the discussion was mediated by a single PDF file containing the 2D project information. The professors appreciated such approach to the project data summary. The participants were easily finding the relevant project information. They also were annotating and sketching using the full screening visualization function (Figure 83).

During the interview, the students were extremely motivated to share their feedback, and despite the low reflexivity scores, emphasized rather positive perception of team social interactions. One of the main uniting elements for them was the idea which was in the core of their design proposal.

Regarding the system usability scale scores, the team members gave either “awful” 37,5 usability score, or the fair scores of 60 and 67,5. Suggesting that one team member did not find the proposed digital table useful at all.

Regarding the collaboration organization, all the team members agreed that it was very useful to keep the same project information as the PDF file, easily navigated by turning pages. They suggested that such single file would also allow to track the decisions, and thus to keep the clear illustration of the project evolution, to avoid the need to open new files. The architecture student S78A reports that: *“The meetings were so short that we did not need to download the annotations screenshots, yet the meeting audio or video would be certainly of use (for reporting).”*

Regarding the organization and the table use they also emphasized the responsibilities assignment: *“In the group we have one person who can use the table, and it will work. I do not use the table well, even if I manage to turn pages.”* (S79T). The other student agrees, and completes that: *“I cannot say that I feel confident or not confident in my skills to use the table, I will be able to display the documents if required, but prefer to delegate.”* (S77C).

From the interactions experience, the student S78A comments that: *“... the navigation touch of the table was more interactive, better, which made us more confident. The hardest part was to put the necessary files on display. I feel confident in my abilities to use it, it is simple and like a big laptop.”* However, the same student emphasizes that there is a need from better precision of the gestures to sketch details, and to use the lines which are less thick.

Regarding the digital documents use, the student S77C comments that: *“... 3D use lacks fluidity of the gestures, but we may replace it with the screenshots of the relevant views”,* thus suggesting the way to adapt the visualization. And his colleague S79T agrees that: *“The 3D use is still complicated on the table, it is necessary to bring the laptop, thus we did not use the 3D but the 2D documents.”*

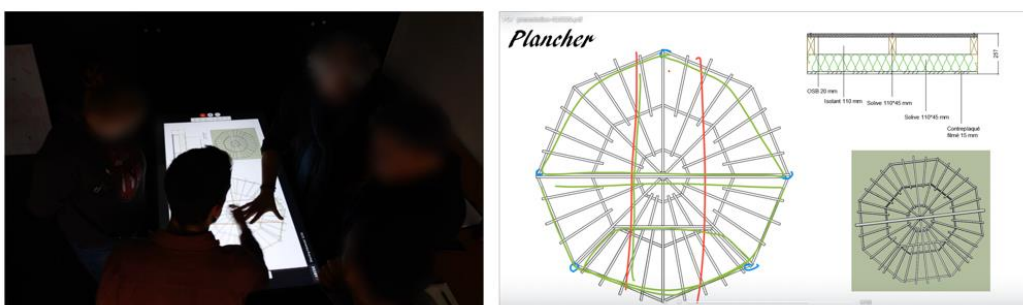


Figure 83 Collaboration session of the team a with the digital collaboration table, presenting Timber challenge project

In addition, on the macro collaborative level, the participants perceived the proposed digital approach and use of the digital mediums for the project review as beneficial, since it allowed:

- *“Different way of working, more collaborative”* (S24A);
- *“Possibility to show documents to everyone”* (S23T);
- *“It fosters to better prepare the mediums and the meetings”* (S93T);
- *“The setting in circle, encouraging discussion and more egalitarian teacher-student relationship, less formal”* (S27A);
- *“United presentation within a single medium”* (S17A).

However, on the macro collaborative level, the participants also requested time and training to feel confident in their skills in digitally-based collaboration; and a more efficient file import and management and adapted for use by several users.

3.1.3.2 Mezzo level of the digital collaboration table use

System Usability Scale scores

In total we have collected System Usability Scores (SUS) from the use of the proposed digital collaboration table for the Timber Challenge from 9 users (participants) in Phase1, from 29 users in Phase 2.2, and from 33 users in Phase 3.2. SUS evaluations from the Design project phases are not included into the following analysis, since the aim of collaboration during the Design project was focused on design, yet the aim of collaboration during the Timber challenge was focused on construction preparations decision-making.

The analysis of the data allowed to distinguish 3 main pairs of user profile categories of population: *students (S) and professors (P)*; with the subcategories for the students by their curriculum: *architects (A), timber engineers (T), civil/other engineers (C)*; participants who consider that they successfully achieved the tasks with the proposed system (*TA*), who consider that they did not successfully achieved the tasks with the proposed system (*TNA*); participants with less than 5 years of work experience (*WE<5y*) and with more than 5 years of work experience (*WE>5y*); (Figure 84). The analysis did not provide evidence to consider the number of 3D use experience as a separate user profile.

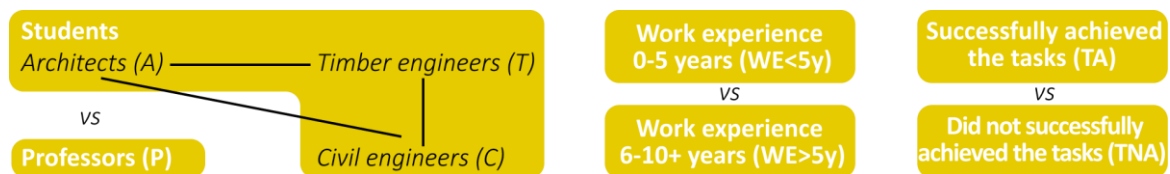


Figure 84 Schematic representation of different participants user profile categories by T-test, KS and MW tests. A continuous line: the scores are consistent with the hypothesis that the groups come from the same distribution.

Despite the low number of participants, we analyzed the data statistically. First, in any participants group larger than 8 we verified whether the score distribution was normal with two tests: Shapiro-Wilk (SW) and D'Agostino's K^2 (DAK²). None of the scores given by architects, engineers, professors, or all respondents together violate the normality assumption (in SW p-value ranging from 0.198 to 0.901, W from 0.933 to 0.983; in DAK² p-value ranging from 0.108 to 0.971, K^2 from 0.051 to 4.43). However, since normality tests are of little power on small size samples, for investigating the similarities and differences between the groups, we did not restrict ourselves to parametric tests (T-test; whether the variance was same or not, decided by an F-test for equal variances - always different in our case), but also conducted two non-parametric ones (Kolmogorov-Smirnov (KS) and Mann-Whitney (MW)).

The professors' group 'P,' who gave the highest scores, stands out from the others: their scores are statistically significantly different from those of C and T, who gave the lowest scores (p-value < 0.01 in all tests). The group that resembles P the most is the architects (A), who came out to be similar to them in the first edition of the study (p=0.580 in T-test, 0.961 in KS and 0.500 in MW test; the statistics t=0.60, F=0.33, U=5.50 respectively) and different in the second one (p-value < 0.05 in all tests, t=-3.92, F=0.80, U=1.50), bringing about mixed results when taken together (different according to T-test and MW, p<0.01, and not dissimilar according to KS, p=0.072). The pairs A and T and C and T are consistent with the assumption that the participants' scores come from the same population. Groups A and C are close to conforming to the similarity hypothesis but not unanimously (similar according to MW, p<0.05, U=19.00, and different according to T-test and KS, p=0.079 and 0.059, t=1.93, F=0.60).

Additionally, we verified the independence of the scores of the group who consider that they successfully achieved the tasks with the proposed system and of those who consider otherwise. All our tests corroborate the difference between these two groups: p-values for T-test, KS, and MW are all less than 0.0001. Moreover, we verified the independence of the scores of participants who with less than 5 years of work experience and with more than 5 years of work experience, with the tests allowing to consider that these two groups are different, also with p-values for T-test, KS, and MW are all less than 0.005.

The SUS mean scores from all categories together were “75” for Phase 1, “61” for Phase 2.2, “60” for Phase 3.2. The previously presented SUS scores interpretation scale (Figure 76) recommends we interpret these scores as *“Good”, “OK”, and “OK”*. Table 23 and Figure 85 summarize the SUS.

The SUS score from Phase 1 is higher with 75 than for the Phases 2.2 and 3.2: 61 and 60. The difference between these scores may be influenced by the population “motivation” difference, since at the Phase 1 the user profile of students was *“innovation eager and curious about technology”*, both student team chose to use the proposed collaboration environment, and during the other phases the use of the environment was mandatory, thus including more user profiles, not necessary sharing such motivation or curiosity about technology. Moreover, the number of participants at the Phase 1 was smaller than at the next experiment phases. The Phase 1 users had fewer sessions, therefore less time and experience with the proposed environment.

Table 23 System Usability Scores summary

| Phase | Pedagogical exercise | Value type | User category | | | | | User background | | | | | |
|-------------------|----------------------|------------|---------------|----------|------------|------------|-----------|-----------------|-------|------|------|-------|-------|
| | | | All users | Students | Professors | Architects | Engineers | Timber Civil | Other | TA | TNA | WE<5y | WE>5y |
| Phase 1 2018 | Timber Challenge | SUS Score | 75,0 | 74,6 | 75,8 | 78,1 | 67,5 | | | | | | |
| | | Deviation | 7,0 | 8,1 | 5,2 | 4,7 | 10,6 | | | | | | |
| | | Count | 9 | 6 | 3 | 4 | 2 | | | | | | |
| Phase 2.2 2019 | Timber Challenge | SUS Score | 61,1 | 57,8 | 79,5 | 59,2 | 56,7 | 53,8 | | | | | |
| | | Deviation | 15,7 | 13,7 | 10,4 | 11,2 | 18,2 | 11,2 | | | | | |
| | | Count | 29 | 24 | 5 | 9 | 9 | 6 | | | | | |
| Phase 3.2 2020 | Timber Challenge | SUS Score | 60,0 | 60,0 | 85,0 | 51,3 | 62,5 | 52,5 | 65,0 | | | | |
| | | Deviation | 15,1 | 13,2 | 5,0 | 13,9 | 8,8 | 14,4 | 15,4 | | | | |
| | | Count | 34 | 31 | 3 | 12 | 9 | 5 | 5 | | | | |
| All participants | | Score | 62,5 | 60,0 | 80,0 | 60,0 | 61,3 | 52,5 | 65,0 | 65 | 42,5 | 60 | 75 |
| | | Deviation | 15,6 | 14,3 | 8,1 | 15,6 | 13,9 | 12,1 | 15,4 | 13,6 | 7,6 | 14,6 | 9,9 |
| | | Count | 72 | 61 | 11 | 25 | 20 | 11 | 5 | 61 | 11 | 57 | 15 |

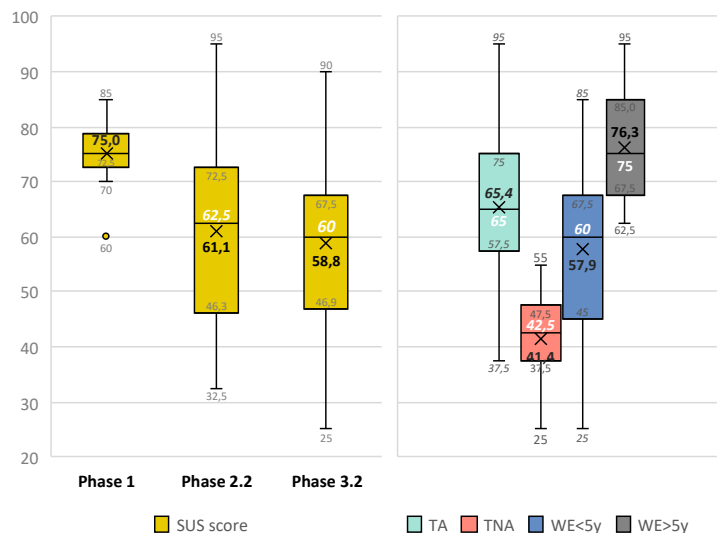


Figure 85 Diagram of the SUS scores values by phase

The *professors provided higher SUS scores than the students*. In Phase 1, the SUS score is 75,8 “good” from all the professors, and it is slightly higher than 74,6 “good” from the students. Both stay close to 75 “good” score, or to the score from all participants for this phase, illustrating a rather homogenous result. Such scores suggest that the users are rather satisfied with the usability of the proposed digital collaboration environment.

In Phase 2.2 the professors’ score was 79,5 “good”, therefore a little higher, than in previous phase. It is to note that professors already had some experience with the digital collaboration environment before. Despite some updates, they still felt confident in the given score. However, the score from the students was 57,8 “OK”, which is significantly lower. The students also had twice as many sessions than their predecessors, and thus had a more long-term and multiple uses perspective. In the Phase 3.2 the SUS from professors was 85 “excellent”, and 60 “good” from the students, this score difference is similar to the scores of the previous phase.

Despite difference in the *background in architecture, timber or civil engineering, the data analysis does not suggest that there is a distinction between these user profiles*, even though the architecture students gave higher scores than the others at Phases 1 and 2.2. Yet, the highest score from Phase 3.2 was from the timber engineers.

The participants who consider that they *successfully achieved the tasks with the proposed system, gave higher SUS scores*. They confirmed that in general, with the proposed system they could perform their actions well (with no obstacles) during collaboration sessions, and represent 80% of all participants. Their mean score of 65 “good”, is higher than 42,5 “OK” from the participants who do not consider that they successfully achieved the tasks. These participants commented that often they perceived the session discussion as very dynamic, and that they did not have enough time (or quick enough reflexes) to rapidly visualize the necessary project documents, which they required as a medium for discussion. Some participants mention that they prefer to use a pen and paper for decision-making. Therefore, there is a need for an analysis of general acceptance of technology and qualitative feedback.

More *experienced participants tend to give higher SUS scores*. The analysis observes a pattern between the number of a user’s years of experience and their SUS score. Almost 20% (15 participants) of all users have more than 5 years of work experience and they tend to give a higher score of 75 “good” than 60 “OK” from the others with less than 5 years of experience. Amongst the users with experience 90% *successfully achieved the tasks with the proposed system*, and amongst the users with less experience 80%. However, 70% of the experienced participants represent the professor’s category, which represents a significant bias, but does not annul the perception of the usability.

Even though the observations suggest that there might be an influence of an amount of 3D model use experience on the SUS scores, with higher score of 76 from experienced, and 55 from than less experienced users, the data analysis did not allow to confirm such influence. Further investigation is required.

On the activity level, the participants perceived the use of the DCT for the project review as beneficial, since it allowed:

- *“It allows more playful, less formal meetings” (S16T);*
- *“Facilitates exchanges by creating an environment dedicated to discussion” (S31T);*
- *“Large screen on which everyone can act and review” (S27A);*
- *“ergonomic dimensions” (S28T);*
- *“appreciated the possibility to access the sketching interaction “on one click” (S97A);*

- “possibility to interact with the documents and to annotate them synchronously with the other users” (S88T).

However, on the activity level, the participants also requested reported various difficulties and concerns:

- “Difficulties with the precision of touch-gesture and sketching, which also made difficult to interpret the annotated documents” (S80A);
- “Interactivity bugs made us use paper for sketching” (S30A);
- “the touch interactions of “zoom” and “scroll” required adjustments” (S32C);
- “collective synchronous interactions confusing when several people were interacting with the documents at the same time.” (S86A);
- “... for example, in a company, it's complicated to fit a 2m long digital table in a construction site office” (S15C).

3.1.3.3 Micro level of the digital documents uses for the project review and 4D BIM use survey

Digital collaboration sessions documents use summary

Various types of the project documents, such as 2D digital documents, 3D models and 4D models, together with the scale models were used at the meetings to mediate project review and assist with decision-making (Table 24, Figure 86). As a main medium for decision making and discussions, the collaboration sessions participants were more inclined to use a 3D model, if it was available. They also tended to use mostly one project document as a decision-making medium, despite any project documents being available or displayed.

For the Timber Challenge at the Phase 1 in 2018, the collaboration session participants were using 2D digital documents representing plans, sections, rendered images, quantifications and 3D models for the project review and construction preparations. ***Only one team used a 4D model.*** However, during the construction, the students preferred to rely on mostly the project documentation printed out on a paper, since they were working in a dusty environment, and since the ***new members, joining the design team for construction, did not feel confident using 3D and 4D.*** Thus, 4D model was consulted only once a day by one member of the team, who administered the ***construction management.*** It allowed him a better understanding of the assembled timber elements and for monitoring of the progress according to the schedule.

At Phase 2.2, during the Timber Challenge 2019, ***all the teams were using the 3D model*** of their project ***as a main discussion medium*** (Figure 87). During the 2 final sessions, ***5 teams used 4D simulations as mediums mostly to illustrate the planned construction sequence,*** yet without detailed review of the planning and construction tasks, serving more as the strategic illustration of the construction method sequence.

Further for the Timber Challenge at the Phase 3.2, all but one teams have used the 3D model as the main medium for decision-making at the weekly meetings (Figure 88). Despite that all the students followed an introductory seminar about 4D BIM simulations, and that the quarter of all students had already worked with 4D, only one of the teams proceeded with 4D integration into their work.

At Phase 2.1, all the teams were using the DCT for the weakly Design project review. ***Only half of the teams (5) was using the 3D models (BIM and not BIM)*** as mediums for decision-making. Once the project design was detailed enough, the students also developed 4D simulations. Some teams have decided to integrate 4D BIM models into the final project deliverables folder (digital) along with the

project plans, sections, 3D model, calculations and quantifications, but they did not necessary use the 4D simulations as mediums at the weekly project review meetings. At Phase 3.1 the teams used the DCT for their weekly project review as well, yet, not all the teams have used 3D models as mediums, but only 6 teams from the 10.

Table 24 Summary of Digital collaboration sessions use of the documents

| Year | Phase | Pedagogical exercise | Number of sessions | Teams number | 2D | 3D | 4D | Scale model |
|------|-----------|----------------------|--------------------|--------------|----|----|----|-------------|
| 2018 | Phase 1 | Timber Challenge | 3 | 2 | 2 | 2 | 1 | - |
| 2019 | Phase 2.1 | Design project | 4 | 5 | 5 | 5 | 2 | 1 |
| | Phase 2.2 | Timber Challenge | 4 | 10 | 10 | 10 | 5 | 6 |
| 2020 | Phase 3.1 | Design project | 9 | 6 | 6 | 6 | - | 6 |
| | Phase 3.2 | Timber Challenge | 2 | 10 | 10 | 9 | - | 7 |

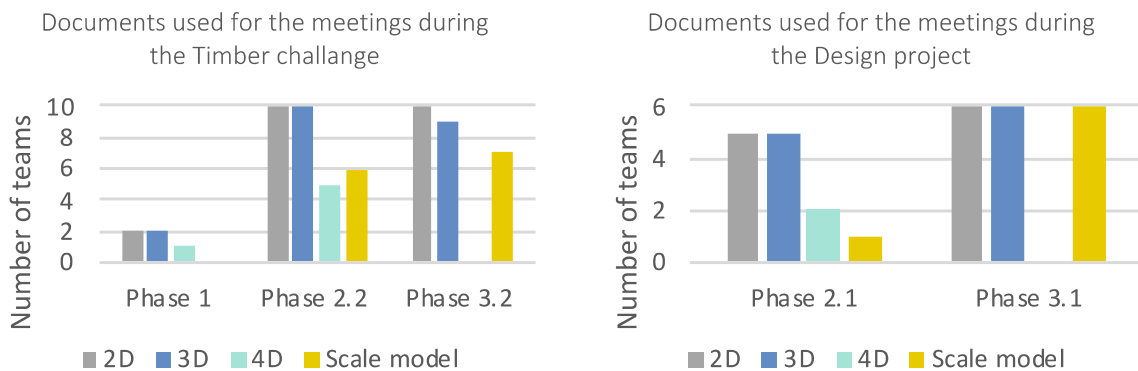


Figure 86 summary of the document types use by the teams at their meetings

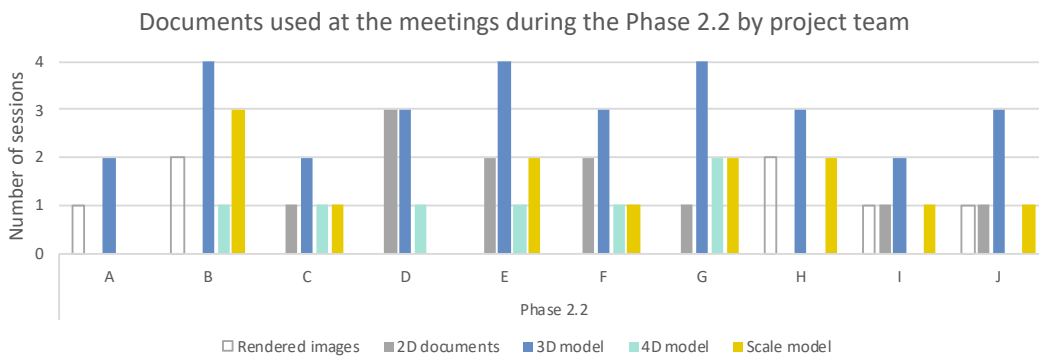


Figure 87 summary of the document types use at Phase 2.2

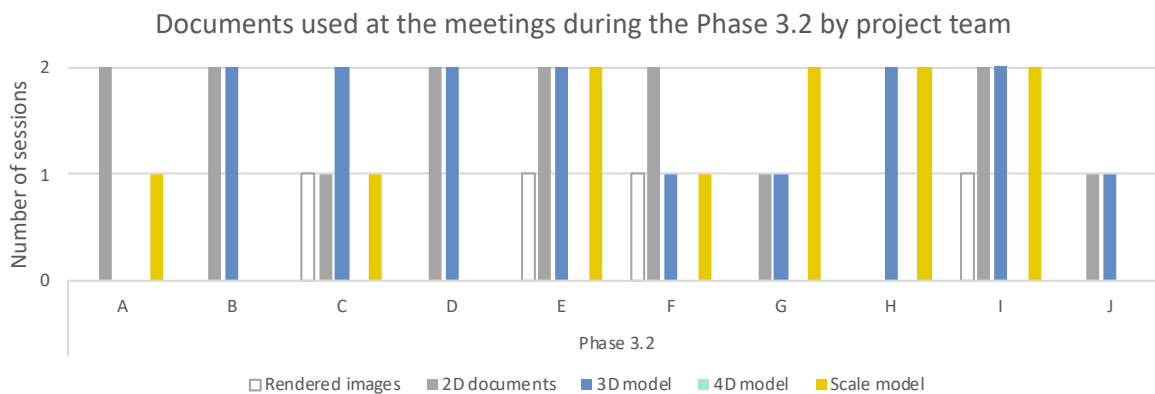


Figure 88 summary of the document types use at Phase 3.2

The participants were asked to evaluate their perceived usefulness of the 3D model of the project as the medium for collective decision making at the meetings, and 90% found it useful. The most often mentioned improvement of the project information and detail visualization quality, was perceived as the major benefit. An architecture student comments, that *"... 3D is useful and allows a good visualization of the project elements for everyone"* (S86A); and his colleague with the civil engineering background adds that the 3D use as a medium for decision making: *"It is quite interesting, especially if you can navigate the project easily. Moreover, all the construction trades should be trained and have a common shared model!"* (S15C). However, the participants have highlighted the need for efficient interactions, a student with the engineering background emphasizes: *"The navigation in the model is not very intuitive. It is lacking possibility to pre-program pre-defined viewpoints to show the models."* (S30A).

The participants emphasized several perceived benefits and concerns from their experience of 4D BIM collaborative use at the meetings. The most often mentioned benefit was about the improved project information visualization quality, like for the 3D models use. Moreover, a student with architecture background comments that: *"The 4D allows to perceive well the construction sequence"* (S13T); a timber structure engineering student comments on the 4D use: *"This allows a good visualization of the progress of the construction site."* (S23T); a student with background in civil engineering provides more general view on 4D, as: *"it's just a digital medium, good for animations, but useful only if the tool is mastered"* (S26C).

Thus, the 4D use concerns highlight the need for the relevant skills, which may not yet be mastered by the project team members. A civil engineering student comments, that the 4D use at the meetings: *"... may be relevant, but we must see who is in charge to provide it, who is trained in design and construction. We must consider that in the companies, we will not always work with young people trained in 3D, but many old people still work in 2D."* (S15C). A student with architectural background highlighted the perceived usefulness, but also the lack of experience: *"It is interesting, we did not use it to its maximum potential. I am not sure that a presentation on a projector would have been less effective. But 4D is very useful."* (S24A). In addition, some participants did not perceive 4D BIM use at the meetings as beneficial, a student with timber engineering background commented that: *"4D has little interest compared to a simple Gantt chart"* (S28T).

On the application and documents level the participants found beneficial:

- *"Efficiency of the presentation visualization and interactivity"* (S13T);
- *"... shared visualization of the 2D and of a 3D, which allows to assure that all the participants are talking about the same thing"* (S13T);
- *"full screen visualization of the plans extremely useful an interactive"* (S27A).

Yet, the participants emphasized the need to allow import of 3D or 4D files, instead of the screen sharing of the 3D/4D modeling applications.

4D BIM use

The 4D BIM use questionnaire aimed to explore the general perception of 4D BIM potential use, yet the investigation in depth perceived usefulness, intention to use or frequency of use would be required for conclusive results. Moreover, most of the student teams did not use 4D BIM for the project development and construction preparations. Yet, the exploration allowed the participants to evaluate 4D scheduling, monitoring, site layout and environment management, safety management, clash detection, constructability management perceived usefulness.

The study gathered answers from 55 participants, all of them were the student team members. The **14 participants (25% of all participants) stated to be already familiar or experienced with 4D simulations** from their previous training or experience. Among those, the most got either an architecture or civil engineering background (Figure 89). Therefore, most participants were rather unexperienced with 4D BIM use experiment participants. However, still some of the participants were familiar with 4D use.

In addition, only 10 of all participants (18%) had more than two years of professional experience, which is typical for the pedagogical context of our experiment, yet allows to gather some data potentially illustrating the ‘young professionals’ perspective on 4D use. The timeframe of two years was chosen due to the possibility to build experience reference frame containing more than one construction project, and work on various project phases. Moreover, **one architect and three civil engineers were familiar with 4D use and had more than two years of experience**. In addition, around a half of all participants had more than two years of experience with the 3D models use (Figure 90), which influences their perception of the 3D use for design and value engineering.

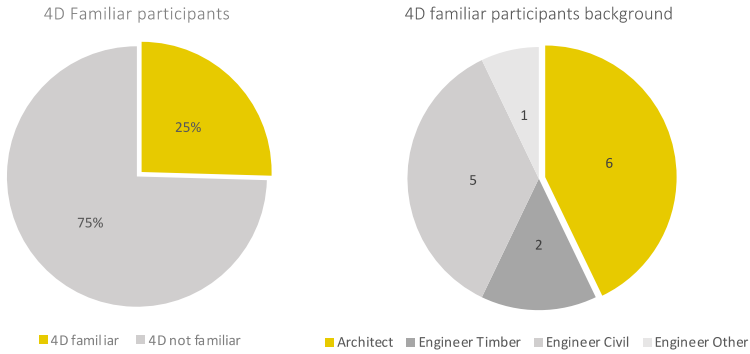


Figure 89 Left: Diagram illustrating the amount of study participants familiar and unfamiliar with 4D, Right: Diagram illustrating the 4D familiar participants background

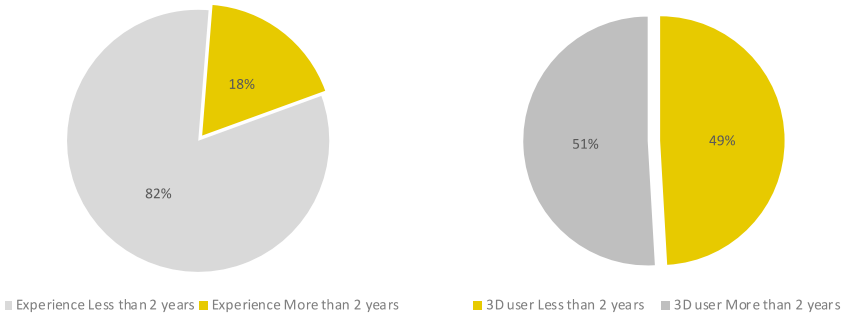


Figure 90 Left: Diagram illustrating the percentage of participants with less or more than 2 years of experience in profession, Right: Diagram illustrating the percentage of participants with less or more than 2 years of experience with 3D modeling

The nature of the gathered data did not allow to run detailed statistical analysis. The data sample size is small, and the data is negatively skewed. However, some observations may be emphasized. Table 25 and Figure 91 summarize the 4D BIM uses analysis. According to the answers from all participants, the 4D BIM Scheduling use gets the highest score of 5 (MD), all the other uses had the score of 4. However, in details the category of participants familiar with 4D familiar gave the highest score of 4.5 to 4D Monitoring, while the 4D Scheduling and other users were evaluated with 4 as well except the safety management which gained the lower point of 3.5.

The participants who are not familiar with 4D provide relatively more positive scores, giving the note of 5 to 4D Scheduling and Clash detection, and the note of 4 to other uses. We observe that regarding the users with no 4D experience tend to give higher scores for all the categories, and perceive more potential in 4D use. The general perception of the usefulness seems to be rather 'optimistic,' yet not all the expectations of the non-experienced with 4D participants correspond to the scores from the 4D familiar participants.

Table 25 4D BIM uses analysis summary

| No | 4D BIM use | | All users | 4D | | Experience | | 3D user | |
|----|--|------|-----------|----------|------------|------------|-----------|-----------|-----------|
| | | | | familiar | unfamiliar | < 2 years | > 2 years | < 2 years | > 2 years |
| 1 | Scheduling | MD | 5 | 4 | 5 | 5 | 4 | 5 | 5 |
| | | STDV | 0,98 | 1,24 | 0,86 | 0,9 | 1,2 | 1 | 1 |
| 2 | Monitoring | MD | 4 | 4,5 | 4 | 5 | 3 | 4 | 5 |
| | | STDV | 1,16 | 1,60 | 0,95 | 1,0 | 1,5 | 1,1 | 1,2 |
| 3 | Site layout and environment management | MD | 4 | 4 | 4 | 4 | 4 | 4 | 5 |
| | | STDV | 1,10 | 1,21 | 1,08 | 1,0 | 1,6 | 1,1 | 1,0 |
| 4 | Safety management | MD | 4 | 3,5 | 4 | 4 | 3,5 | 3 | 4 |
| | | STDV | 1,26 | 1,28 | 1,27 | 1,2 | 1,5 | 1,2 | 1,3 |
| 5 | Clash detection | MD | 4 | 4 | 5 | 5 | 3,5 | 4 | 5 |
| | | STDV | 0,98 | 1,14 | 0,92 | 0,9 | 1,2 | 1 | 1 |
| 6 | Constructability management | MD | 4 | 4 | 4 | 4 | 4,5 | 4 | 5 |
| | | STDV | 1,14 | 1,21 | 1,13 | 1,10 | 1,37 | 1,13 | 1,12 |

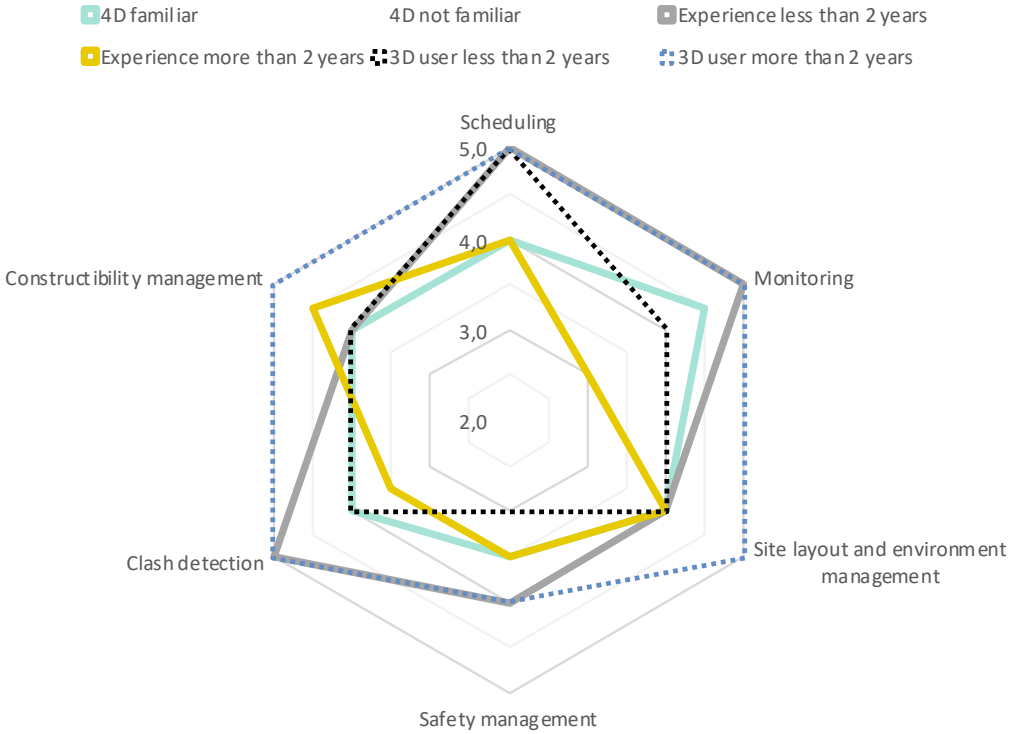


Figure 91 Summary of 4D BIM uses evaluation by participant category

The less experienced participants have evaluated Scheduling and Monitoring with the highest scores of 5. However, the more experienced participants gave the score of 4 to the Scheduling and the score of 3 to Monitoring. In addition, the less experienced participants also perceive the Clash detection as the most useful 4D BIM use. The more experienced participants however gave a higher note to the

Constructability management, than the less experienced participants. With further studies, this may be investigated to outline the perceived 4D BIM use value by the experienced professionals. The participants with more than two years of experience in 3D modelling gave the most 'optimistic' evaluation to the usefulness of 4D BIM for all the used, except the Safety management; while the participants who are less experienced with 3D modelling gave one-point lower scores to all the uses, except the 4D BIM Scheduling.

This summary did not aim to present the quantitative results, but to highlight the potential of the observed tendencies. Further investigation with an extensive data gathering tool and a larger data sample would provide more conclusive results.

3.1.3.4 The pedagogical potential

The professors were the initiators of the DCT use and experimenting. Naturally, the focus for them was on teaching and pushing students to design and construct the best possible projects in a collaborative way. Therefore, *optimization of use of the DCT was not in their primary focus*. Because of this, the pedagogical team was available to provide feedback on digital collaboration table usability from the similar to the students' point of view. Yet, they provided feedback on the changes that DCT brings to the design process, its benefits and challenges.

In addition to the usability feedback, the professors emphasized their pedagogical point of view on DCT implementation into teaching design and construction to multi-disciplinary teams.

The professors emphasized that the *implementation of such tool fostered more active participation and interactions at the meetings*. They highlight that the implementation allows a certain clarity of *visualization and democratic user interface interactions*, since all the meeting participants are united around the table and share the same project documents. The students also mention the general "playful curiosity" and "*reduce the student-teacher barrier*" aspects as the new experience from the project review meetings.

The *shared view* allowed professors to have access to the project documents and assess the design progress. Moreover, with such tool students prepare better their project documents for the meeting, and they do not stay in front of their laptops but are expected to participate at the decision-making. This is beneficial for better project understanding, and use and development of the student skills.

The professors perceive that with the DCT as a medium for project review, they have better access to the project documents and interactivity, thus they consider that they provide *better and more thorough feedback on the projects*.

The pedagogical team agrees on one of the main advantages of the DCT, it is the *ease of visualization and interactions with 3D and 4D models for any kind of user*. Not all the members of multidisciplinary teams are familiar with 3D modeling, therefore the 2D documents are still in the core of early design process mediating communication within the team, and allowing an equal ease of contribution. However, the professors outlined that even with only a 3D model of the project as the meeting mediator for the Timber challenge, such medium provides enough information about the project.

However, the current setting and the collaboration approach did not offer to structure the meeting discussion with a tasks list, nor did it offer easy project planning for further development and design tasks assignment. Therefore, most of the student teams leave the session with unstructured feedback, which does not allow to maintain the information continuity, record decisions and transform them into

the task lists. The professors suggest changing *the session collaboration session scenario*, by adding time to summarize the decisions and plan the future session with the tools which would be integrated into the DCT.

The professors also suggest the need to instruct students more about digitally based multidisciplinary collaboration practices. The table, as a medium of collaboration, fosters new ways of working together, therefore it forces to change the habits of design practices, and reveals the need to adapt for digital collaboration workflows. The future pedagogical strategy must focus on the *development of the digital collaboration culture in the multidisciplinary student teams*, so the students would be able to form reflexive efficient teams and adapt to multidisciplinary workflow. In summary, professors' feedback may be emphasized as

- *Benefits from the use of a 3D model as "a single source of project information";*
- *Benefits from the interactive use of 3D model by multidisciplinary teams as a medium for decision-making;*
- *Benefits from more efficient pedagogical feedback on the designs;*
- *Need for efficient decision recordings, and automated tasks assignments at the end of the meeting;*
- *Need to foster more collaborative and integrated practices during the studies.*

Results emphasis

The Timber challenge design and construction pedagogical exercise provided a context to study digitally mediated synchronous collaboration at the weekly project review meetings. In total, we surveyed collaboration of 22 multidisciplinary student teams who worked on their micro architecture projects. Since the students were first developing the project design and preparing construction, and next building the projects, it gave a real project scale to the project. The implemented mixed data gathering tools allowed to study the digital collaboration from the perspective of the macro level, the digitally mediated activities during the meetings from the perspective of the mezzo level, and the digital project documents, 3D/4D models use as the collaboration mediums from the micro level perspective.

The collaboration analysis revealed the perceived need to enhance collective digital tools use, and the organization of the digital design process, as well as to develop the relevant skills. The students also emphasized the need to maintain the digital data flow, and automate meeting preparations and records. This is consistent with the previously identified requirements.

The team reflexivity study allowed to distinguish 3 different types of teams: resilient teams with the high task and social reflexivity (the less present type 18%), complacent teams (most of the teams 47%) with low task reflexivity but high social reflexivity, and dysfunctional teams with low task and social reflexivity (35%). The resilient teams were more effective, open to innovation and focused on the problem solving; the complacent teams are not aware of the ways they make decisions, and not effective in their tasks, nor much interest in innovation, yet they still have the average well-being inside the team; the dysfunctional teams had poor task effectiveness, member well-being and innovation. The results of System Usability Scores (SUS) from the use of the proposed digital collaboration table for the Timber Challenge, suggest that the tool is usable, but still has to adapt to the users' needs. More experienced participants tend to give the higher SUS scores. Amongst the users with experience the 90% successfully achieved the tasks with the proposed system.

Various types of the project documents, such as 2D digital documents, 3D models and 4D models, together with the scale models, were used at the meetings to mediate project review and to assist with decision-making. As a main medium for decision making and discussions, the collaboration sessions participants were more inclined to use a 3D model, if it was available. The participants emphasized that the quality of visualization and possibility of democratic interactions as the main benefits of the proposed digital tool.

The professors were the initiators of the DCT use and of the experiment. According to them, the table, as a mediator of collaboration, fosters new ways of working together. It encourages to change the habits of design practices, and reveals the need to adapt for the emerging digital collaboration practices and study their workflows. The future pedagogical strategy must focus on the development of digital collaboration culture in the multidisciplinary student teams.

Summary of Chapter 3

Experimenting with BIM/4D and NUI use for synchronous collaboration and decision-making

- Within the presented pedagogical context, we were able to evaluate the usability and learnability of a digital collaboration table from the perspective of active and frequent users in the context of real construction projects (small timber structures), and to outline the user interactions with digital project documents during collaboration sessions. In our study the users' interactions with the digital collaboration table were categorized as: visualization, manipulations, and annotations.
- The users proceeded with manipulations of 3D/4D models mainly for project presentation and to change the 3D model point of view, to annotate it with the collaboration decision. Sketching and annotations were used to support the identified issues solution proposition and to suggest modifications, however not every session benefited from the annotation function. Naturally, users accompany their session with discussion (verbal communication), pointing, and mimicking gestures. Most of the student teams left the session with a great deal of unstructured feedback they would not naturally implement efficient collaboration practices. So, the students would be able to form reflexive and efficient teams and adapt to multidisciplinary workflow.
- User activity analyzed during a collaboration session shows that the 3D model is primarily the focus of discussion and therefore requires for easy and natural interaction. Also, the users tended to solve all the questions with only one document as a decision-making medium. Therefore, uniting all project information in the same digital core may prove benefited not only for the digital dataflow continuity, but also for more interactive collaboration.

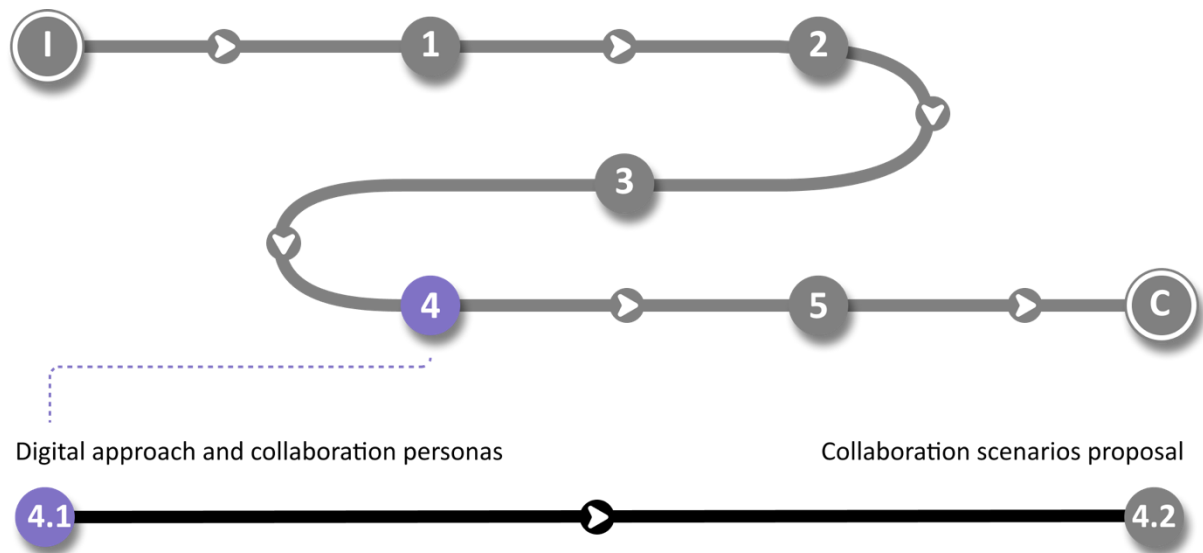
Chapter 4.

Scenarios proposal for BIM based collaborative co-located decision-making

In the context of prototyping, we developed a proposal of collaboration scenarios in correlation with the type of a project meeting (collaboration session), and the 4D Lean Board prototype as an interactive application to assist AEC professionals with decision-making during the sessions.

The chapter is shorter in comparison to the other thesis chapters, yet it emphasizes the separate result of the investigation, moreover, the scenarios represent a tool guiding the User-centered design and our further prototyping.

First, it seeks to portray the relevant elements for the collaborative BIM-based decision-making, and emphasizes the 4D BIM uses and project roles, collaboration styles, and proposes a summary of a collaboration persona representing the actor of the collaborative activity mediated by the digital tools (4.1). Second, it proposes the collaboration scenarios making use of 4D BIM and Lean schedule level in relevance to the collaboration goals and project development, and concludes with the summary of a pre-construction collaboration session scenario (4.2).



4.1 Digital approach and collaboration personas

4.1

4.2

4.1.1 Digital approach to BIM-based collaboration outline

4D BIM uses and project roles

Every construction project is unique, since it has its own specific program and site, with relevant legal frame and consultants and construction team structure. However, despite the specifics defined by every project, a generic model may be proposed with a predictable *pattern of the core project workflow* components and stakeholder involvement to describe collaboration.

Naturally, all AEC professionals focus on their responsibilities, thus they prioritize the activities which would be relevant to their role in the project delivery. Hughes et al. present a summary of the essential aspects required for collaboration from different construction role perspectives. The summary presents that regardless of the role, *an open dialogue environment between all parties with a clear outline and understanding of the roles and responsibilities* is valued by most of the study participants (Hughes et al., 2012). This emphasizes that not only roles are essential for efficiency of the project tasks, but they impact collaboration quality as well.

Tauriainen et al. analyze the design management practices in a context of BIM and Lean Construction, and emphasize the *importance of BIM manager responsibility* among others define design responsibilities, to structure and foster collaboration culture. They suggest that Lean tools use like the Big room, the Target value design and the Last Planner System could assist the coordinator with such responsibilities (Tauriainen et al., 2016). Yet, their focus was on the design activities, and did not extend to other activities.

A study of project planning proposes a meta-process model describing project workflows and the workflow relevant data, and a mockup of a dialogue support system and its use scenario for computer mediated collaborative decision-making. But first, the study illustrates the workflow pattern by listing project activities and relevant access rights to project data. In the proposed summary the Owner, Consultant, Design-Builder, Architect and Contractor have four possible rights of data access, which may be either: *writable* (to be filled in or can be edited); *read-only*; *system-generated* (design-time or deduced from user database); *transition-channeling* (used to direct workflow) (Verheij, 2005). The study proposes a detailed matrix of activities and responsibilities, providing an example of the roles pattern, yet it focuses on project planning, and not on construction planning.

With the emergence of BIM various effort seek to propose tools organizing collaboration and effective information management. For example, British Standards Institution proposed for BIM Level 2 the roles, responsibilities and authorities to be summarized with the Responsibility Matrix assigning the roles for specific activities, such as: *responsible, accountable, consulting, informed* (BSI Standards Publication, 2013). Such tool provides the project team with a framework for collaboration, and specifies the inputs required from the project team members. Yet, each BIM use requires different roles and responsibilities (Hardin and McCool, 2015).

A study by Boton et al. focuses on *collaborative scheduling activities*, and emphasizes that an architect provides a list of building elements, a construction supervisor defines activities and develops

a schedule, a contractor sequences activities, sub-contractors estimate activities duration (Boton et al., 2011b). The emphasized processes may be also interpreted as responsibilities.

Another example of the pattern and responsibilities modeling is a study of protocols for Collaborative Design Processes by Kassem et al., who emphasize stakeholder involvement and responsibilities regarding various BIM uses, with the responsibility types as: *responsibility, shared responsibility, input*. For the BIM use of *4D planning* they outline that the *Contractor is mainly responsible* for such use, and *Client, Architect, Civil/Structural Engineer, MEP Engineer all provide input* (Kassem et al., 2014). Such analysis illustrates distinction of responsibility and input for the planning.

Thus, a variety of studies explored and emphasized the roles and responsibilities of different project team members from different perspectives. Our study focuses on synchronous co-located collaboration and 4D BIM collective use. Therefore, we summarize *the actors (project team members)* involvement and influences of actors in such scope with Table 26, Table 27, Table 28. The tables suggest nuanced accountability of actor roles based on their impact of the decisions based on the previous studies of collective decision-making proposing categories of:

- *responsible:*
 - *validator (VA),*
 - *coordinator (CO),*
- *participating:*
 - *producer (P),*
 - *consultant (C),*
 - *reader (R) (Halin et al., 2002).*

The proposed roles aim to illustrate generic patterns and assist with the collaboration scenario portrayal, as well as for the 4D BIM collaboration tool development. The actors use 4D BIM and interact with it in different ways depending on their responsibility and the project phase. However, the 4D BIM use for project information visualization has a transversal role in the project life cycle, and it mediates the other 4D BIM uses. The tables list different roles that actors can fill during different project phases. The construction manager role is listed in a separate column, since in the French AEC context architecture firms, engineers or consultants may carry it, and not necessarily only contractors. Moreover, Client and Project manager roles are united as well. Each of these roles has specific duties and responsibilities, varying slightly from one to another. These vary from understanding expert information to reading a presentation. Each role supports different phases of a project (Bolshakova et al., 2019). Additionally, other uses of 4D BIM can benefit from these roles, as with producer, consultant and reader.

Naturally, every project role and responsibility is defined by the project's legal contract and delivery approach. For example, as summarized in Table 26, Table 27, the 4D BIM use of 4D Scheduling may prove to be useful at both Design and Pre-construction phases, and naturally extend to the Construction phase, in the context of a more collaborative project delivery method. Thus, in case of collective 4D Scheduling, to forecast construction phases and sequencing, first the dialogue between the client and project management launches the project, and engages the consultants from the design team such as architects and engineers. Further, the project client and management have validation and consulting responsibilities, but the decision-process stands on the experience of the design team, where the other project team members also contribute with their expertise to foster more collaborative and efficient decision-making. For example, the BIM manager establishes the framework for collaboration and coordination, and the Construction manager together with the Contractor may consult as well. Further,

during pre-construction phase, all the expertise converges, and more of the leading responsibilities shift from the design team to construction team (Table 27).

Table 26 Design phase 4D BIM uses and actor roles, influences & interactions

| Design phase with Approximate LOD | | | | | | | | | | | | | |
|---|-----------|------------------------|----------------------|-------------|-----------|-----------------------|--------------|------------|----------------|----------------|------------------------|-----------------------|-------------------|
| 4D BIM use | Role type | Actors | | | | | | | | | | | |
| | | Client/Project manager | Construction manager | BIM manager | Architect | Civil/Structural Eng. | MEP Engineer | Contractor | Safety manager | Subcontractors | Manufactures Suppliers | Construction Surveyor | Quantity surveyor |
| 4D Scheduling | | | | | | | | | | | | | |
| - Forecast construction phases and sequencing | R P | VA C | | CO | VA P | VA P | VA P | | | | | | |
| - Optimize the construction schedule with the CPM | R P | | | CO | VA P | VA P | VA P | | | | | | |
| 4D Clash Detection | | | | | | | | | | | | | |
| - Detect spatio-temporal conflicts | R P | | | CO | VA P | VA P | VA P | | | | | | |
| - Detect static and dynamic conflicts | R P | | | CO | VA P | VA P | VA P | | | | | | |

Responsible R: VA –Validator, CO – Coordinator; Participant P: P – Production, C – Consultant, R –Reader

Table 27 Pre-construction phase 4D BIM uses and actor roles, influences & interactions

| Pre-construction phase Precise LOD | | | | | | | | | | | | | |
|---|-----------|------------------------|----------------------|-------------|-----------|-----------------------|--------------|------------|----------------|----------------|------------------------|-----------------------|-------------------|
| 4D BIM use | Role type | Actors | | | | | | | | | | | |
| | | Client/Project manager | Construction manager | BIM manager | Architect | Civil/Structural Eng. | MEP Engineer | Contractor | Safety manager | Subcontractors | Manufactures Suppliers | Construction Surveyor | Quantity surveyor |
| 4D Scheduling | | | | | | | | | | | | | |
| - Forecast constr. phases and sequencing | R P | VA C | | CO | VA P | VA P | VA P | CO P | | | | | |
| - Optimize constr. schedule with CPM | R P | | | CO | VA C | VA C | VA C | CO P | | | | | |
| 4D Clash Detection | | | | | | | | | | | | | |
| - Detect spatio-temporal conflicts | R P | | | CO | VA P | VA P | VA P | | | | | | |
| - Detect static and dynamic conflicts | R P | | | CO | VA P | VA P | VA P | | | | | | |
| 4D Safety Management | | | | | | | | | | | | | |
| - Analyze structural safety issues | R P | VA C | | CO | VA C | VA C | VA C | CO C | | | | | |
| - Identify safety issues | R P | VA C | | CO | | | | VA P | CO C | | | | |
| 4D Constructability Management | | | | | | | | | | | | | |
| - Design temporary works | R P | | | CO | CO | CO | CO | VA C | VA C | | | | |
| - Test different construction alternatives | R P | C | | CO | CO | VA | VA | VA C | | | | | |
| - Optimize interfaces management | R P | | | CO | CO | | | VA P | VA C | | | | |
| 4D Site Lay-out & Environment Management | | | | | | | | | | | | | |
| - Anticipate environment conflicts | R P | | | CO | CO | | | VA P | | | | | |
| - Forecast workspace conflicts & coordination | R P | | | CO | CO | | | VA P | R C | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|----|---|---|---|---|----|--|---|---|--|--|--|
| - Adjust the schedule during the construction | R | | CO | | | | | VA | | | | | | |
| | P | R | P | C | C | C | C | C | | R | C | | | |

Responsible R: VA –Validator, CO – Coordinator; Participant P: P – Production, C – Consultant, R –Reader

Table 28 Construction phase 4D BIM uses and actor roles, influences & interactions

| Construction phase and Detailed LOD | | | | | | | | | | | | | | |
|---|-----------|--------|---------------------|-------------|-----------|-----------------------|--------------|------------|----------------|----------------|----------------------|----------------------|-------------------|------------------|
| 4D BIM use | Role type | Client | construction manage | BIM manager | Architect | Civil/Structural Eng. | MEP Engineer | Contractor | Safety manager | Subcontractors | Manufactures Supplie | construction Surveyo | Quantity surveyor | Facility Manager |
| | | | | | | | | | | | | | | |
| 4D Safety Management | | | | | | | | | | | | | | |
| - Analyze structural safety issues | R | VA | CO | CO | | | | VA | CO | | | | | |
| | P | | C | | P | C | C | P | P | R | | | | R |
| - Identify safety issues | R | VA | | CO | | | | VA | CO | | | | | |
| | P | | C | | | C | C | | | R | | | | R |
| 4D Constructability Management | | | | | | | | | | | | | | |
| - Design temporary works | R | | CO | CO | | | | CO | VA | | | | | |
| | P | | P | | C | C | C | | | | C | | | R |
| - Test different construction alternatives | R | | CO | CO | | | | CO | | | | | P | |
| | P | C | | | C | C | C | | C | | | | | |
| - Optimize interfaces management | R | | CO | CO | | | | CO | VA | | | | | |
| | P | | P | | P | P | P | P | C | | C | | | |
| 4D Site Lay-out & Environment Management | | | | | | | | | | | | | | |
| - Anticipate environment conflicts | R | | CO | CO | | | | CO | | | | | | |
| | P | | P | | P | P | P | P | C | R | C | | C | R |
| - Forecast workspace conflicts & coordination | R | | CO | CO | | | | CO | | | | | | |
| | P | | P | | P | P | P | P | C | R | R | | | |
| - Adjust the schedule during the construction | R | | CO | CO | | | | CO | | | | | | |
| | P | R | P | | C | C | C | C | C | R | R | | | |
| 4D Monitoring | | | | | | | | | | | | | | |
| - Give short term goals to construction team | R | VA | CO | CO | | | | CO | | | | | | |
| | P | C | P | C | C | C | C | P | C | R | R | C | | |
| - Record real progress, compare to schedule | R | | CO | | | | | CO | | | | | | |
| | P | C | P | C | C | C | C | P | R | R | R | R | C | R |
| - Adjust the schedule during the construction | R | | CO | | | | | CO | | | | | | |
| | P | C | P | C | P | P | P | P | R | R | C | R | | |

Responsible R: VA –Validator, CO – Coordinator; Participant P: P – Production, C – Consultant, R –Reader

In summary, a variety of roles and responsibilities are required to provide their expertise and input during collaborative project development, with authorization and coordination input required from the different actors. Since the responsibilities evolve with the project evolution, the collaboration protocols and tools must be adapted as well, to provide the actors with the most efficient means to achieve their goals. The research timeline and resources did not allow us to validate the proposed summary with various AEC experts, and is limited to the summary from the literature and the review from the academic community. From the UCD perspective, such emphasis of the users' responsibilities allows better understanding of the user needs and guides the interactions design.

4D BIM uses and project documents

Once the actors relevant to decision-making are identified, they must be provided with the relevant project documents to mediate collaboration at the meetings. With the 4D BIM-based collaboration the model is in the core of the group activity, yet not all the necessary information elements are included into the model directly. Therefore, Table 29 summarizes the project documents which may prove to be

relevant to collaborative decision-making in correlation with project phase and 4D BIM use. With digitally developed projects, some elements of the information may already be part of the digital data workflow, and be referenced in the project database or online cloud service, or even be part of a 5D model.

Table 29 4D BIM uses and Project documents for decision-making support

| | 4D BIM use | 4D Model | Project documents |
|---------------------------------------|--|--|--|
| Design phase Approximate LOD | 4D Scheduling | <i>3D models from early design to design development</i> + <i>Time management program or planning, milestones and phase sequence with estimation of time and resources</i> | Site assessment (plans, permits, environment, soils study) |
| | - Forecast construction phases and sequencing | | Program and budget from client |
| Design phase Approximate LOD | - Optimize the construction schedule with the CPM | | Project specifications Project principal stakeholders Construction methodology choice General requirements on project delivery, program Calendar events Collaboration protocol |
| | 4D Clash Detection | | |
| Design phase Approximate LOD | - Detect spatio-temporal conflicts | | Models assembled |
| | - Detect static and dynamic conflicts | | Rules of conflict detection Estimations of charges Collaboration protocol, roles, charts |
| Pre-construction phase Precise LOD | 4D Scheduling | | Site preparations (plans, permits, environment, soils study) |
| | - Forecast construction phases and sequencing | | Project volume, specifications and quantifications Methodology specifics of constructing technology techniques, tools, competences Plans and technical details of the project Detailed requirements on project delivery Project stakeholders' roles and interventions limits Stakeholders' calendars and recourses Collaboration protocol, roles, charts Economic and management risks and quantifications |
| Pre-construction phase Precise LOD | - Optimize the construction schedule with the CPM | | |
| | 4D Clash Detection | <i>3D models with design established and detailed</i> + | Rules of conflict detection Plans and technical details of the project Construction methodology details |
| Pre-construction phase Precise LOD | - Detect spatio-temporal conflicts | <i>Time management planning, including milestones, phases and construction tasks scheduling</i> | Estimations of charges Collaboration protocol, roles, charts |
| | - Detect static and dynamic conflicts | | |
| Pre-construction phase Precise LOD | 4D Safety Management | | Site preparations (plans, permits, environment, soils study) |
| | - Analyze structural safety issues | | Project volume, specifications and quantifications Construction methodology details Plans and technical details of the project Project stakeholders' roles and interventions limits Stakeholders' calendars and recourses Collaboration protocol, roles, charts Security protocols, contracts, insurances, controls Requirements on project delivery Safety control protocols Economic and management risks and quantifications |
| Pre-construction phase Precise LOD | - Identify safety issues (work at heights, moving objects, etc.) | | |
| | 4D Constructability Management | | |
| Pre-construction phase Precise LOD | - Design temporary works | | Quantifications and supply update Construction methodology details |
| | - Test different construction alternatives | | Update on human and tools recourses Project stakeholders' roles and interventions limits Stakeholders' calendars and recourses |
| Pre-construction phase Precise LOD | - Optimize interfaces management | | Collaboration protocol, roles, charts |
| | 4D Site Lay-out & Environment Management | | |
| Pre-construction phase Precise LOD | - Anticipate environment conflicts (traffic flows, pedestrian, etc.) | | Security protocols, contracts, insurances, controls Requirements on project delivery Safety control protocols |
| | - Forecast onsite workspace conflicts & subcontracts coordination | | |
| Pre-construction phase Precise LOD | - Adjust the schedule during the construction | | Economic and management risks and quantifications |
| | 4D Safety Management | | |
| Construction phase Detailed LOD | - Analyze structural safety issues | | Project log, reports, photos, scans, exchanges Updates on construction terrain with work progress details |
| | - Identify safety issues (work at heights, moving objects, etc.) | | |
| Construction phase Detailed LOD | 4D Constructability Management | <i>3D models initial and ongoing, as-build</i> + | Quantifications and supply update Construction methodology details |
| | - Design temporary works | <i>Time management as a precise dynamic construction scheduling</i> | Update on human and tools recourses Project stakeholders' roles and interventions limits Stakeholders' calendars and recourses |
| Construction phase Detailed LOD | - Test different construction alternatives | | Collaboration protocol, roles, charts |
| | - Optimize interfaces management | | Security protocols, contracts, insurances, controls Plans and technical details of the project Requirements on project delivery Economic and management risks |
| Construction phase Detailed LOD | 4D Site Lay-out & Environment Management | | |
| | - Anticipate environment conflicts (traffic flows, pedestrian, etc.) | | |
| Construction phase Detailed LOD | - Forecast onsite workspace conflicts & subcontract coordination | | |
| | - Adjust the schedule during the construction | | |
| Construction phase Detailed LOD | 4D Monitoring | | |
| | - Give short term goals to construction team | | Project log, reports, photos, scans, exchanges |

| | |
|---|--|
| - Record real progress and compare it to the schedule | Requirements lists (e.g., responsible construction firm, materials, equipment) |
| - Adjust the schedule during the construction | Collaboration protocols, contracts Economic and management risks |

4.1.1.1 Decision-making types and collaboration persona

Collaboration sessions for decision-making

The project team encompasses different AEC professionals carrying various roles and responsibilities, and engaging in various interactions. For a collective activity, knowledge and competencies of every individual team member are important. The implementation of BIM and integrated delivery approaches fosters the use of collective knowledge, skills and competencies as parts of collective intelligence of the project team. The current study focuses not on individual, but on group interactions for collaborative decision-making activity.

In order to describe such collective activity, we propose to implement the collaboration persona (CP) approach (Judge et al., 2012), which is derivative from the User persona method, also called Individual Persona, which represents a tool of user-centered design. According to Judge et al., “*collaboration personae are empirically derived descriptions of hypothetical groups of people with specific qualities, goals and needs.*” (Judge et al., 2012). Thus, CP describes a type of persona which focuses on the collective group goals and needs of the group, which is the project team united for a meeting in our case. CP also encompasses the aspects describing collaborative work, since the collaboration group internal influences and subordination must be considered as well, because “*collaboration personas include individual personas (playing the roles), who enact scenarios at different phases of the collaboration*” (Matthews et al., 2010). Matthews et al. (Matthews et al., 2011) developed a CP based on collaboration types:

- *dynamic project team,*
- *stable project team,*
- *customer-supplier relationship,*
- *committee,*
- *community and professional relationship.*

These collaboration types have features which portray CP dimensions, such as:

- *goals (group tasks and motivation),*
- *group members (if the members are stable or dynamic),*
- *work style and leadership style (designated or democratic), etc.*

The UCD and CP approach suggest implementing such tools as real work observations and guided interviews with a focus on group members to emphasize the elements relevant to the dimensions. The CP approach allows to describe the needs and collaboration of groups of users (actors), as well as their interactions among actors and goals. From the interactions design perspective CP provides a tool allowing to consider different actors’ roles throughout their collaboration process, and to be more *focused on the group needs and interactions* (Bornet and Brangier, 2015).

Thus, we propose a summary of AEC project collaborating groups (Table 30), which are united by the main group goals defined by the project development phase. The proposed summary also illustrates the relation of collaboration type to decision class. The work on a construction project is accomplished by different professionals, who take their project roles, and contribute their expertise as members of different groups to the achieve goals. We also implement the group collaboration types proposed by Matthews et al. into the summary, who summarizes the types and their descriptions with dimensions

of personnel, workstyle, leadership (Matthews et al., 2011). The groups are generic, and naturally depend on the project type and legal frame. All collaboration groups are motivated by the goal as a constant element in long-term, most groups contain more than three members. With digital and integrated approaches to project delivery, BIM represents a technological core for the project team members who are guided and coordinated by BIM and integration management.

Naturally, the development of a construction project begins with collaboration between clients, project managers and design team who emphasize the project program and requirements for the design production in a client-supplier collaboration style and focus on project policy decisions and management. The design phase is rather characterized by democratic collaboration style in a stable team occupied with pooling and co-creation. Starting from the pre-construction phase, the project team becomes more dynamic with designated leadership, also they continue the decision order from Management to Operation and then Control.

Table 30 Main characteristics, collaboration styles and decision-making classes study

| Phases: Program - Design | | Phases: Pre-construction - Construction | | | | | | | |
|---|--|---|---|---|---|---|--|--|---|
| Group main characteristics | | | | | | | | | |
| Group 1 | Group 2 | Group 3 | Group 4 | Group 5 | Group 6 | Group 7 | Group 8 | Group 9 | |
| Name | Project program | Project design | Design management | Pre-construction management | Construction design | Construction management | Construction production | Construction control | Safety management |
| Members | Client/Project manager Architects Engineers | Architects Engineers BIM manager | BIM manager Architects Engineers | Construction manager Architects Engineers Client/Project manager Contractor | Construction manager Contractor Architects Engineers | Construction manager BIM manager Contractors Architects Engineers | Construction manager Contractor Subcontractors | Construction manager Contractor Architects Client/Project manager | Safety manager Construction manager Contractor Architects Engineers Client/Project manager |
| Main goal | Emphasize the project program and requirements approve design production | Design the project and the BIM model | Control and manage the project design collaboration and BIM | Prepare, coordinate and survey the project pre-construction phase | Design the project construction documentation | Manage the project construction documents and efficient teams' collaboration | Build the quality project matching to the program and requirements | Prepare, coordinate and survey the project construction phase | Manage the project construction site security over the construction process |
| Group collaboration style | | | | | | | | | |
| Collaboration type | Client-supplier | Stable team | Committee | Client-supplier | Dynamic team | Committee | Dynamic team | Dynamic team | Dynamic team |
| Personnel | Stable | Stable | Stable | Dynamic | Dynamic | Stable | Dynamic | Dynamic | Dynamic |
| Workstyle | Communication focused | Pooling & Co-creation | Pooling & Co-creation | Communication focused | Pooling & Co-creation | Pooling & Co-creation | Pooling & Co-creation | Communication focused | Communication focused |
| Leadership | Designated leaders | Democratic | Democratic | Designated leaders | Democratic | Designated leaders | Designated leaders | Designated leaders | Designated leaders |
| Group decision-making class | | | | | | | | | |
| Decision class | Policy | Strategic | Tactical | Policy | Strategic | Tactical | Operational | Tactical | Tactical |
| Decision system role: inside system role | | | | | | | | | |
| | Management: Approving | Operation: Co-operating | Control: Supervising | Management: Coordinating | Operation: Co-operating | Control: Supervising | Operation: Co-operating | Control: Supervising | Control: Supervising |

Collaboration Persona

Collaboration groups, which summarize the features of collaboration persona, may benefit from different 4D visualization and other uses, for example the Project design team and Design process team may implement 4D Scheduling and Clash detection. Further, these uses are implemented for Pre-construction management by Construction design and Construction management teams, who also benefit from 4D Safety, Site lay-out, Environment, Constructability management. The Safety management team mostly benefits from 4D Safety management, and the Construction production team mainly benefits from the 4D Monitoring and Construction management.

Further, we outline an example of Collaboration Persona “Construction management team” (Table 31) using 4D BIM as a mediator from collective decision-making. The proposal is based on common practices of project development and BIM implementation guides and protocols, and interviews with AEC professionals.

Table 31 Collaboration Persona “Pre-construction management team”

| | |
|------------------------------|---|
| Name: | “A-project” construction management team |
| Context: | a large public building project “A-project” development with BIM and IPD approaches |
| Project phase: | pre-construction |
| Goal: | Prepare and coordinate construction phase |
| Roles: | Managers, Architects, Engineers, Contractor, Subcontractors, etc. |
| Workstyle: | communication with a BIM model is in the core of collaboration, evolves with the project from client-designers dialogue to interdisciplinary collaboration |
| Tasks: | <ul style="list-style-type: none"> - identification of project limits - establishment of the basis and progressive development of schedule management - design the project development process - assure project deadlines and the basis for construction monitoring, etc. |
| Needs: | <ul style="list-style-type: none"> - strict aims and objectives of the program - an access to a digital workflow - work protocol - BIM methodology - technological core, interactions system, etc. |
| Skills and knowledge: | related to the role’s skills and knowledge, BIM and integrated practices understanding, collective intelligence and professional experience |
| Dependences: | Inside the group a Design team of architects and engineers assures design tasks and decision mediation, while construction management and production are in dialogue with them, with client and project management contributing to the collaborative decision-making |
| Decision-making: | Policy and Strategic classes, focused on management: co-operating |
| 4D BIM use: | 4D BIM model containing detailed 3D and schedule, as a collaboration and decision-making support for 4D Scheduling, Clash Detection, Safety Management, Constructability Management, Site Lay-out & Environment Management |

4.2 Collaboration scenarios proposal

4.1

4.2

4.2.1 Scenarios describing activities

Scenarios use in AEC research

In the AEC domain the term “scenario” is often associated with the design scenarios, the constructability assessment and construction methods scenarios comparison, the data exchanges scenarios or contractual scenarios for BIM.

The scenarios are not only implemented for user experience design, but various studies in the domain of AEC research implemented the use scenarios as a tool to describe an activity, and to adapt the novel digital tools development to the users’ needs.

For example, a study proposing a prototype of a dialogue support system for process-mediated planning describes the system use with the use scenario (Verheij, 2005). Another study investigates multidisciplinary cooperation and in the context of the meta-model developing and prototyping of a *multi-user views interface also considers scenarios* as a tool to describe collective activities (Kubicki et al., 2006).

Following the similar needs to adapt the project documents visualization to the specific stakeholders needs and work tasks, another study investigated the use of 4D models by different AEC disciplines for different purposes, and developed a diverging-sequential *4D color scheme, considering different work scenarios* which adapt the color scheme to the user needs, thus providing guidance to the interface design (Chang et al., 2009).

In addition, Gu and London emphasize that despite the common misconception among AEC professionals that BIM adoption requires to redesign and adjust the whole work process, only some *BIM use scenarios relevant to specific parts of the project lifecycle* may be implemented (Gu and London, 2010). Further, for development of the rules and regulations, the use scenarios are also considered while developing the IFC exchange protocols and *Model Views Definition, as the end-user scenarios* in addition to the data exchanges protocols (Karlshøj et al., 2012).

Woessner and Kieferle compare the *scenarios of BIM collaboration in Virtual Environments*, which are encompassing the co-located and distant collaboration settings and different technical tools. The study focuses on the relevant equipment description and interaction gestures evaluation. The study proposes *usage scenarios as a means to categorize BIM tools*, and summarizes “Merge and Coordinate” scenario example with BPMN (Woessner and Kieferle, 2016).

Therefore, several works implemented scenarios as a tool describe BIM and collaboration activities, as well as to emphasize different aspects relevant to more efficient and user-centered digital tools and work processes design.

Scenario as a tool for UCD

In our research we consider the scenario from the UCD perspective as a tool to describe activities and allowing to adapt the proposed design and prototyping to the users' needs. The UCD proposes different tools to *document stakeholder needs and emphasize design ideas*. *The user stories, personas, and scenarios* are examples of conceptualizations of stakeholder needs.

The purpose of the scenarios is to guide UCD and development of the novel tools, which present the interactions designers with tools for : *"... simply writing down and discussing a few key expectations about users' goals and experiences will enhance a shared vision of the problems and opportunities facing system users."* (Rosson and Carroll, 2002). Thus, they allow to evaluate some challenges and highlight the further uses. They also serve as the description of the use situations, they help the designers: *"... to understand and to create computer systems and applications as artifacts of human activity, as things to learn from, as tools to use in one's work, as media for interacting with other people"* (Rosson and Carroll, 2002). Thus, in a scenario-based design, descriptions of how people accomplish tasks are a primary working design representation. The software designing is fundamentally about envisaging and facilitating new ways of working, activities and tools. The continuous focus on use situations for human work and activity promotes learning about the structure of problem domains (Carroll, 2003).

Thus, the scenario *does not describe a step-by-step user action as a use-case*, but it describes:

- *collaboration context and project phase,*
- *activity actors,*
- *activity goals,*
- *mediators of the activity such as digital documents, collaboration software pre-sets of the interface view and options, with features offered to users to answer a collaboration session goal.*

Also, we focus on prototype design in the context of the BIM-based collaboration as a socio-technical system (macro level), the digitally based collaboration for collective decision-making activities (mezzo level-structure). The design must enhance usability of the prototype for a larger scope of user profiles, and allow a possibility to mediate different tasks embedded into the activities (micro level). According to Norman within an activity-centered design, *the activity defines the product and its structure* (Norman, 2013). Thus, a conceptual model of activity shapes the design solutions and enhances HCD.

4.2.2 Scenarios proposal summary

Collaboration scenarios proposal

The collaboration process and tools adapt to the development phases of a construction project. They are also shaped by the specific activities of design development, value engineering and decision-making. The development and implementation of scenarios into the prototyping helps users to articulate the existing work practices and express the envisioned use of the prototype (Preece et al., 2015), and further guide the UCD design aiding to define pre-sets and features of the 4D-based collaboration prototype adapted to specific collaboration scenarios. From the AEC point of view the collaboration scenarios correspond to the project team meetings (collaboration sessions) purposes and follow the project development phases.

It is important to emphasize that every project is unique, and project phases, actors and processes are adjusted to the specific needs. Yet, for the collaboration environment development and description

of the collaborative activities we propose four main collaboration scenarios, corresponding to the four general stages of the project development, BIM model LOD and Lean schedule levels (Figure 92).

The first scenario corresponds to the early stages of project development with the project identification and design program outline. The BIM model level of development is very low, and rather conceptual since the design activities are not yet started. Yet, the general ideas of project volumes and intervention zones, as well as the existing on-site conditions such as topography, networks, existing buildings and construction regulation limitations may already become a basis for the 3D modeling. The main dialogue would be between the client or client representatives, or project managers and the design team members, typically architects, who emphasize the project program and requirements, and approve the design production. Moreover, the main project milestones may already be outlined, defining estimated construction start, main business, design and construction milestones, as well as the delivery date.

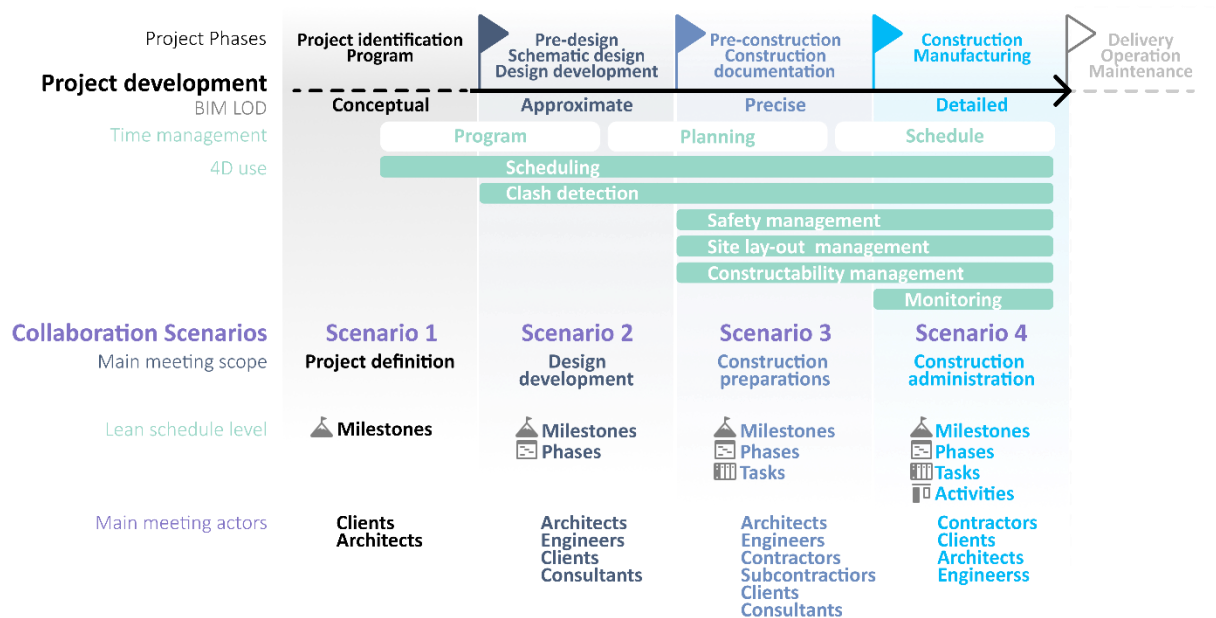


Figure 92 Collaboration scenarios schema

The second scenario corresponds to the project design development stages with the BIM model being in the core of the design activities and gaining precision to approximate level of the model, and even precise for many projects. The project design evolves and is emphasized with BIM 3D modeling. The main dialogue would include the client and the design team, with possible inputs from contractors of other consultants as integrated team members. In addition to the milestone, the construction sequence may be summarized with the Phases level of the Lean schedule. The 3D and time management information allow to benefit from 4D BIM scheduling and clash detection uses, adapted to the project information level of detail.

The third scenario continues to augment the project information complexity and 4D BIM uses, as well as the number of collaboration actors. It corresponds to the pre-construction preparations development stage, with the BIM model in the core of more construction management related activities, and providing the precise level of detail. The project design is validated and completed. The main dialogue would transfer the leading roles from the design and project management experts to the construction consultants collaboration with the design team, client and the external consultants. At this stage not

only general planning but also detailed scheduling is required, the Lean schedule level of the 6 weeks look ahead schedule managing tasks, crews and requirements corresponds to the collaboration needs of the scenario. Since the project BIM model and schedule are linked, the 4D BIM scheduling and clash detection uses may be completed with safety management, site lay-out management, constructability management and construction monitoring 4D BIM uses.

The fourth scenario corresponds to the construction phase, with the detailed BIM model in the core of more construction management. The main dialogue is between contractor and subcontractors, as well as the design team, a client and the external consultants. At this stage all the levels of Lean schedule are required including the daily construction activities level. All these elements shape the collaboration requirements. All 4D BIM uses are of service, with 4D BIM construction monitoring as the main use. The outlined scenarios emphasize the available information, project goals and main actors which would be relevant to the design of the 4D-based collaboration tool.

Pre-construction scenario as the user-centered design tool

To guide the development of the novel digital tool and adapt it to the different scenarios needs, we describe Pre-construction scenario with 4D BIM and Lean scheduling use as the mediums for collective decision-making from the UCD perspective, as an example:

A-project construction management team (collaboration persona) design and construction professionals prepare the construction phase of a large public building project “A-project”. The project development relies on BIM, Lean Construction and IPD approaches. The contractors and subcontractors are leading the project with their technical lead, and the design team completes the set of knowledge and skills required for the decision-making. The team uses a digital collaboration environment as their activity mediator. It is comprising a touch table and screen allowing natural interactions with the collaboration software enabling interactions with the 4D BIM model from the project server. The interface of the software is designed to visualize relevant to the meeting goals with the Lean schedule information, and foster collective touch interactions (Figure 93).



Figure 93 Pre-construction scenario: use of the digital collaboration environment

During their pre-construction preparation meeting focusing on the strategic sessions (Table 30) the team does construction sequence review and evaluation of the construction tasks, Charles the Contractor/Construction manager and planner and Anna the Architect/BIM manager coordinate the activity with the 4D BIM schedule review. Tom and Tovi trades and zones managers, and Clara the Client/Project manager are present as well. The meeting duration is two hours— one hour for reviewing the 4D simulation, and one hour for adjusting the schedule. First, the team reviews the Master plan and construction phases sequence before the evaluation of the construction tasks with the look-ahead schedule. The view also allows to verify the tasks assigned to crews and necessary requirements (dependencies, materials, information, safety, equipment, etc.).

The review is collective, so that everyone may benefit from the 4D BIM scheduling and be on the same page regarding outstanding tasks and issues affecting project timelines. By synchronizing their actions during this meeting, Charles and Anna assured the construction take-off readiness, and identified the required information flow. Charles, Tom and Tovi have saved hours of back-and-forth communication and ensured that their teams are working towards a common goal. The session concluded with validation of the construction phases sequence and the first version of the look-ahead schedule to be completed during the meeting with the last planners.

Summary of Chapter 4

Digital synchronous co-located collaboration scenarios proposal

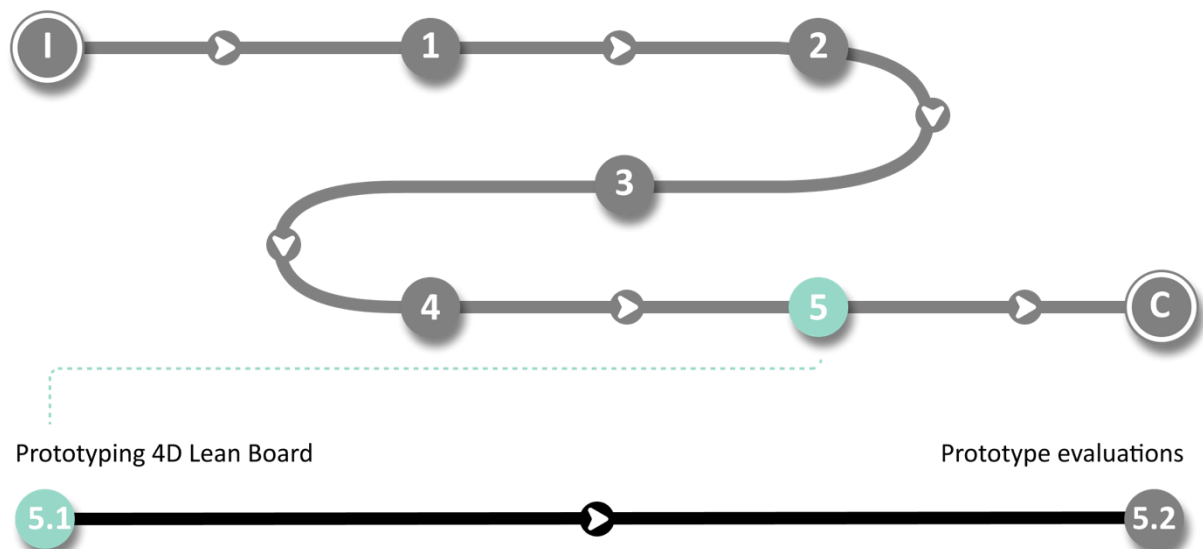
- The complexity of AEC projects and associated collaboration processes and activities requires for a clear conceptualization of the decision-making processes, of the roles of every project team member and as well as the impact of the decisions. Therefore, we identify cooperation group personas, decision-making types and roles.
- The implementation of collaboration group personas allows the interaction designers to consider different actor roles throughout the collaboration process. Every type is described with dimensions: goals (group tasks and motivation), group members (if the members are stable or dynamic), work style and leadership style (designated or democratic), etc. Study suggests CP approach within an alteration to BIM specifics, with a correlation to different problems encountered by the professionals' workgroups.
- 4D BIM use would be relevant for mediation of different collaboration situations. Collaboration groups may imply various 4D BIM uses according to the phase of progress of the project. For example, the proposed 'Project design team' and 'Design process team' on a design phase may use 4D Scheduling and Clash detection. The Construction team may benefit from 4D Visualization for a better communication.

Chapter 5.

Prototyping and evaluating “4D Lean Board” tool

This chapter describes the design and development of 4D Lean Board application’s prototype, and it presents a proposal of its implementation into a digital synchronous co-located collaboration session in correlation with the collaboration scenarios. The prototyping is guided by the previous requirements identification from the literature, the pedagogical experiment results and summary of the collaboration group persona and scenarios.

First, the chapter describes the context of 4D Collab research project of 4D Lean Board design and development as a part of 4D Collab research project, and introduces the 4D Lean Board key features. Second, the chapter outlines the application design and development framework and workflow. Next, the chapter presents detailed overview of the application interface features. Further, it describes the prototype evaluation and concludes with emphasis of the participants feedback and perspectives for future research.



5.1 Prototyping “4D Lean Board”

The following section describes the prototyping process of 4D Lean board. First, it presents the research context of the “4Dcollab” project to outline the background for the studies and solutions influencing the strategy to the prototype development (5.1.1). Such outline is essential in order to emphasize design choices and exploration directions. Second, the section proceeds to the 4D Lean Board proposal outline. It describes the development process of and the main features of the 4D Lean board prototype (5.1.1).

5.1

5.2

5.1.1 Prototyping context and framework

5.1.1.1 Context of the 4DCollab research project

HCI and a digital system for 4D-based collaboration

A team of specialists from different fields led the research of the 4D Collab⁵⁷ project. The multidisciplinary team worked on the research project’s main aims and tasks. One of the results of the research was a prototype of a HCI information system⁵⁸ *4D Collab*. Figure 94 summarizes the link among the applications. It encompasses the components:

- a digital platform⁵⁹ which is comprised of the 4D Collab Service and 4D Collab Navigation Tool, 4D Collab Decision Tool⁶⁰ as a part of 4D Collab lead prototyping;
- a single-page web-application, 4D Lean Board, as an alternative exploration path for the tool.

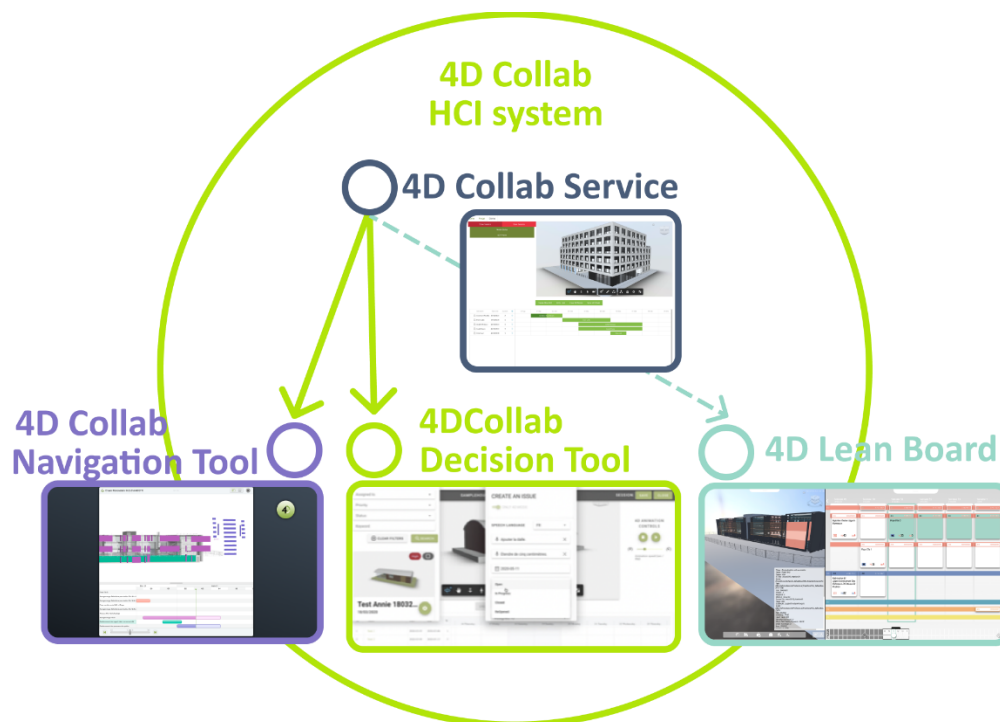


Figure 94 HCI information system 4D Collab: 4D Collab Service, 4D Collab Tool and 4D Lean Board

Yet, all the application prototypes follow the purpose to mediate decision-making at a project meeting (collaboration session). They are still united by the main core concepts, but they each investigate different aspects of a 4D-based collaboration prototype proposal.

In the current context we use the term “*prototype*” as “*a manifestation of a design that allows stakeholders to interact with it and to explore its suitability*” (Preece et al., 2015). Its function is to emphasize a set of system and application features. Naturally, prototypes and use scenarios proved to be effective tools for ideas exploration in HCI and UCD.

Such a multifocal approach to prototyping helps to explore a larger variety of *ideas and hypothesis with fewer constraints* than in a one complex system. It also benefits from a variety of competences from every member of the prototype development teams. Each application prototype focuses on a specific part of the synchronous collaboration process, and is adapted to a particular phase of a construction project. In addition, every application was constrained by technical limitations each approach to the prototype development chosen by each development team.

4D Collab Service and 4D Collab Decision Tool key features summary

4D Collab Service first proposes an ontology representation of a Synchronous Collaboration Session (SCS) with co-located collective decision-making and 4D BIM use-cases (Boje, Bolshakova, et al., 2020). The *4DCollab ontology model* encompasses classes that refer to the SCS, IFC and 4D concepts (see Boje, Bolshakova, et al., 2020). It also introduces a concept of “*4D model object*” by combining the 3D and schedule information.

Second, 4D Collab Service’s development work aims to provide a base for a collaboration support which should set a semantically rich and knowledge-driven environment (Boje, Bolshakova, et al., 2020). The environment should provide access to construction project data at both the collaboration session level, and for the construction project design and development workflow. Considering this, 4D Collab Service features are emphasized through *a graphical web-based interface* (Figure 96).

From the user point of view the interface allows a user to *prepare the 4D model for a collaboration session*. First, the interface offers to upload an IFC file with the 3D model to an online server (powered by Autodesk Forge⁶¹ platform) and it next visualizes the 3D information from the IFC model. Then it offers to add tasks to a schedule on the same web page (i.e., simplified Gantt), where the IFC is already visualized. Finally, it allows the user to create the 4D model objects by linking the schedule tasks to 3D elements of the model. The interface views with the corresponding to the steps in Figure 95. Further, the session’s input data is saved, and thus the 4D model is ready for the synchronous collaboration session.

From the software developer point of view, 4D Collab Service creates *the system’s back-end* that makes all the above-mentioned user actions possible and gives the other developers *access to the 4D*. It implements the 4D Collab ontology model, creates a server to store 3D and 4D data, and offers an API to provide the access to them. Furthermore, the ideas of work on 4D Collab Service went beyond 4D BIM, and they have initiated research about the use of already explored semantic data environment and the web-based linked data to foster use of digital twins in other research works (Boje, Guerriero, et al., 2020).

Following the development of the service as a back-end service, the 4DCollab Decision Tool (Figure 96) offers to the users a web-based interface adapted to the technological context of Shariing (see 3.1.1.2) and allows the users to run 4D simulation, evaluate project schedules and annotate the project model, as well as create the meeting reports.

Landing page

Session creation

4D object creation



Figure 95 The landing page, session creation and 4D object creation pages of 4D Collab Service

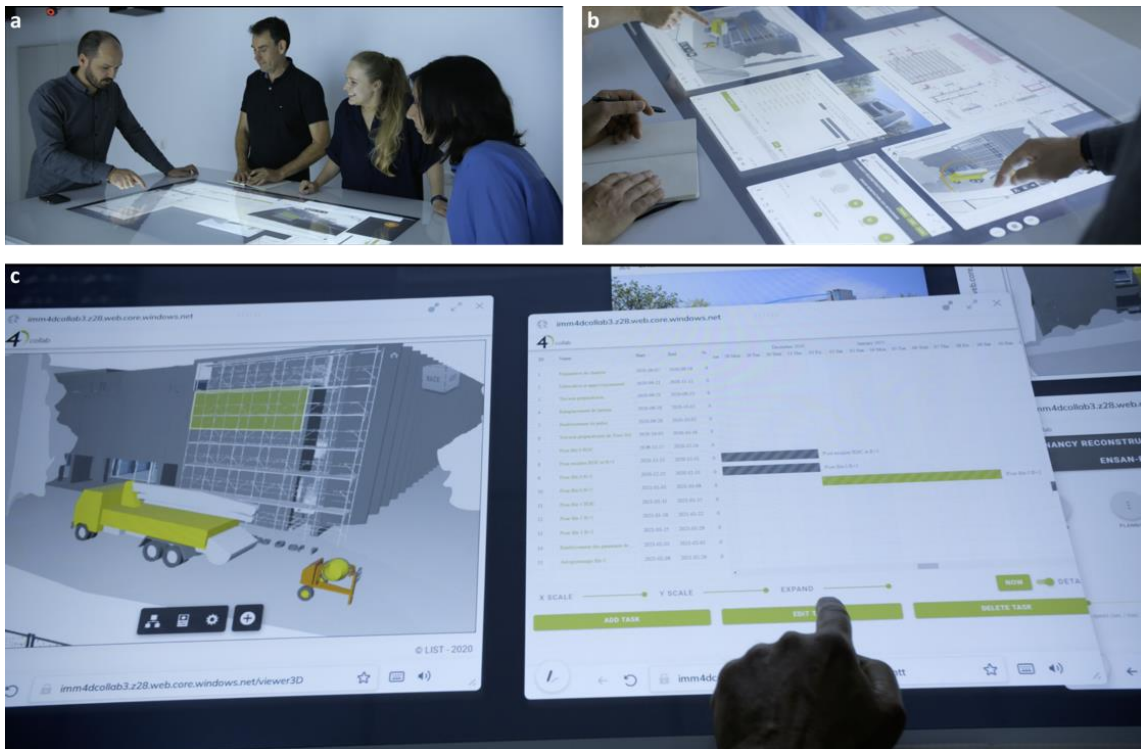


Figure 96 4D Collab Decision Tool collaborative use: a. touch-table use as a mediator for collaboration b. Sharing interface displaying project documents c. 3D model view with the selected element connected to the task and Gantt chart

4D Collab Tool key features

4D Collab Tool relies on the input from the preparation phase of the 4D-based synchronous collaboration session with 4D Collab Service, but the application implementation at the SCS and its development is primarily focused on the front-end part of the platform. Even though the application explores many aspects, the main purpose of this prototype is to evaluate the quality of the visual aspects of a proposed interface, and to *identify the clearest ways to highlight the 4D connection* of the 3D elements to the tasks. A clear 4D visualization would provide a well-adapted digital support for more efficient decision-making during the SCS. Figure 97 displays a summary of the 4D Collab Tool interface.

The 4D Collab tool's development goal is to offer AEC professionals (the users) a 4D model visualization, and have an interface *with the most natural and simple touch interactions* with project information and 4D. Thus, the application retrieves the 3D and 4D information from 4D Collab Service, and integrates it into the graphic interface on the touch-table.

The interface provides to the users a visualization of two views, a 3D view of a construction project model and a view of a schedule (Gantt chart). The Gantt schedule was chosen by the development unit as the most common schedule representation among current AEC practice types. Also, the *Gantt schedule would help to explore the collaboration situations* that are easier for understanding and reflection to the majority of AEC professionals. Alongside the display of 4D visualization, the interface also offers touch interactions with the two views. The research on optimization of the technical solution resulted in relatively *fluid and optimized interactions* and a high response speed on the touch table. The collaborative aspect of multi-touch interactions is considered as well.

From the technical point of view, the development approach was not connected to the web-based tools and technologies, but it relied completely on the “Cocoa”^{xv} object-oriented application programming interface, which offered more flexibility and customization possibilities than web-based approaches.

Finally, in addition to the navigation interactions and 4D visualization, the users have the option to *adjust the schedule during the SCS*, and therefore to compare different schedule versions and their impact on a 4D simulation.

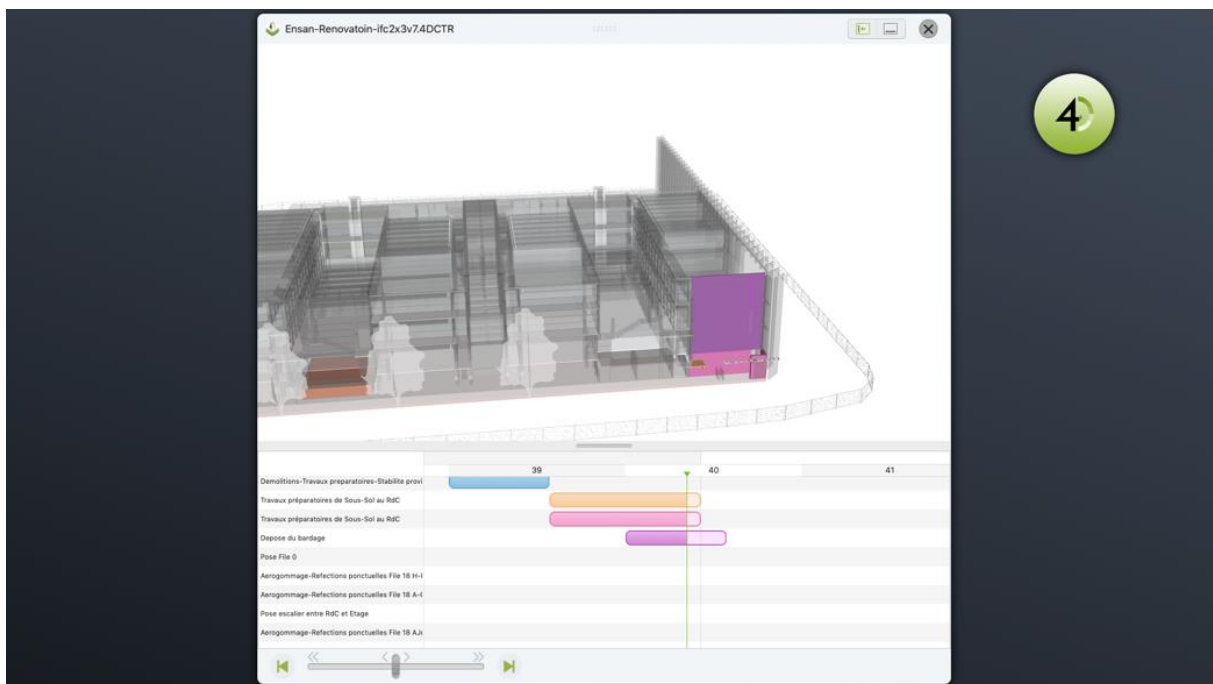


Figure 97 4D Collab Tool interface on the touch table

Introducing 4D Lean Board: key features and purpose

The prototype of *4D Lean Board* (a single page web-application) provides its' users with a *visualization of construction project 4D simulations, and it offers them a Natural User Interactions (NUI) interface to support their decision-making* at the project meetings. Figure 98 displays a 4D Lean Board interface summary, with the 3D model view on the left and scheduling view on the right.

The 4D aspect (key feature) of the prototype offers *a connected 3D model to the lean schedule* which includes an interactive summary of milestones, phases and tasks of a construction project. In addition,

^{xv} “Apple” products native object-oriented application programming interface for macOS.

through the Lean aspect, it offers the multiple types of scheduling representations with a necessary amount of information and details. The interface is developed for *touch interactions* with the information, such as 3D manipulations (move, zoom, pinch) and reviewing the schedule. Also, it is adapted for a large touch-table and for synchronous group interactions, thus it diverges from the classic single-user mouse or touch-pad interactions.

The project view *adapts to a collaboration session types* thus it offers the possibility to adapt the 4D view to user’s needs, to a meeting purpose or to a project development phase trough these multiple levels of schedule detail and 3D styles. This also provides the possibility to have clearer and more simplified 4D without overcharging the view with information that is less useful for decision-making. Figure 99 illustrates a visual summary of the introduced key features of 4D Lean Board. More detailed overview of the features is presented further in 5.1.1.

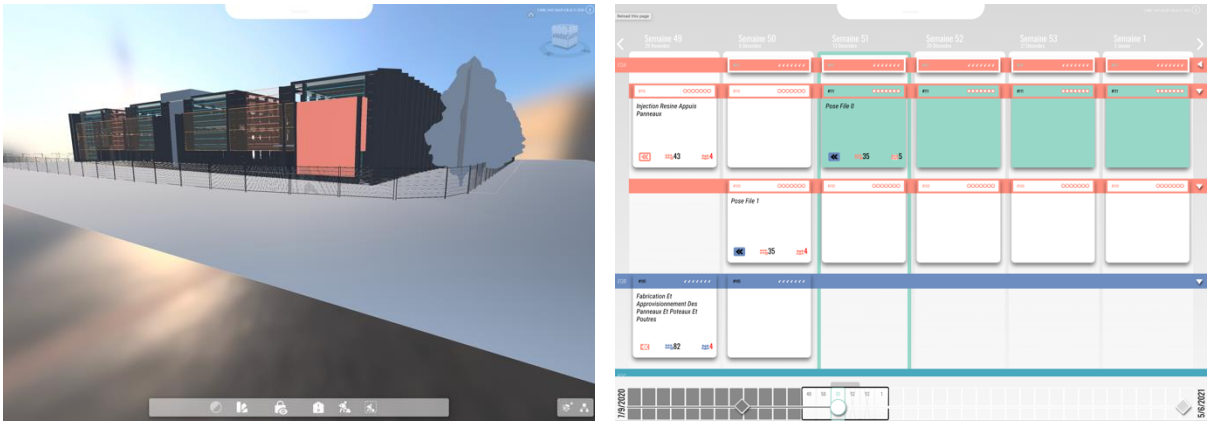


Figure 98 4D Lean Board interface with 3D model on the left and scheduling with milestones and tasks on the right

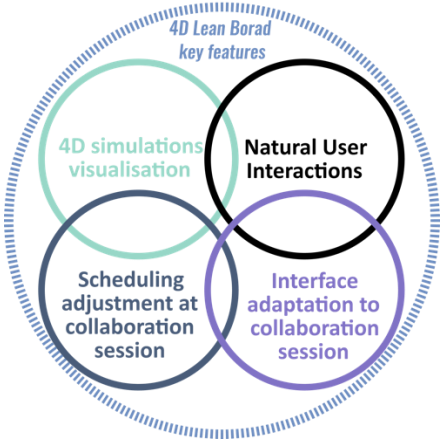


Figure 99 Schematic representation of 4D Lean Board prototype’s key features

Basis for choosing the web development

The research context of 4D Collab project sets not only the research goals and aims, but also sets a technology frame to the prototyping of the abovementioned components, and naturally, to the 4D Lean Board. For example, the *use of a multi-touch table* (digital collaboration table DCT described in chapter 3.1.1.1) for a co-located synchronous collaboration session is a first basis.

Then, following the scope and technological means of the research project, the *use of Shariing software at a collaboration session* as a main digital collaboration environment (application) is the next basis, which is adapted to multi-user multi-touch interactions. It sets a possibility to untie users around the touch-table without a need to choose one side of the table, since Shariing can provide each user with a *copy of a “framed view”* and recognize the multiple-user touch-gestures with the table, and with a connected Shariing session on another display.

As a brief reminder, Shariing^{xvi} provides users with a shared collaboration environment that *offers a shared visualization and annotations of the same document in a framed view*. Through the shared views there is a possibility to open 2D documents, such as pdfs or images to visualize project plans, details, sections, scheduling or a web page, also there is a possibility to open a 3D model or a video file.

The prototype development team chose an approach of integration of *4D Lean Board as a web page framed view into the Shariing*-based collaboration session on DCT. This approach keeps the Shariing’s software code and architecture independent since they already fulfill their main purpose. The web-based application choice for 4D Lean Board basis offers a certain *autonomy and flexibility to the programming and development process*. The web-based prototype also brings the 4D collaboration to a current configuration of the digital collaboration environment with the touch table, vertical screen and “Shariing” software rapidly, and it helps the development team to focus on 4D Lean Board specific features, without reconstructing the existing digital collaboration environment structure or functions.

Together with an easy integration into a SCS with Shariing, the web-based development approach opens a possibility *to access the prototype on any screen with a maintained connection of the 4D Lean Board views*. For example, 4D Lean Board can be opened not only on a touch-table during SCS, but also on an additional vertical screen, and thus it would offer a possibility to provide users with a more detailed view of 3D or 4D models. It can be also accessed from a personal device, such as an iPad, which would still remain connected to the main session on the DCT, since the *views are synchronized, and all the interactions are synchronized* as well.

In addition, the web-based approach maintains the direct *link of 4D Lean Board with 4D Collab Service*, by working with the same core concepts and building the architecture around Forge by Autodesk framework.

4D Lean Board similarities and distinction from 4D Collab Service and Tool

In previous paragraphs we have briefly described the main features of the developed solutions. The description helps first to explain the global context of the development, and second to highlight better the place of 4D Lean Board in the presented research context.

4D Lean Board prototype development, as the abovementioned components:

- *is developed* in a scope of use of 4D for a synchronous collaboration with the multi-touch table;
- *uses Shariing* from Immersion collaboration environment *for the multi-touch table to provide users with multiple copies of the 4D Lean Board web-page view, also Shariing helps to provide multiple user interactions and visualize other project documents aside, and even to make simple annotations;*
- *relies on the concepts and elements of the 4D Collab ontology, which describe a 4D-based synchronous collaboration session;*
- *uses Autodesk Forge web-based platform APIs and services to visualize 3D and add some basic interactions features to the 3D view;*

^{xvi} For more detailed description of Shariing features see 3.1.1.1

- preserves the link and accessibility of the project information from IFC files;
- explores the 4D-based collaboration session, user’s needs and technology limitations.

Despite sharing many key elements and concepts, 4D Lean Board has some distinctions, thus it:

- proposes to explore the 4D visualization in case of Lean approach to the project development, thus the scheduling data is structured differently than Gantt;
- seeks to offer an adapted tool to a larger collaboration scenarios frame than the preconstruction phase;
- explores “control board” approach to the 4D view and interactions development;
- includes an additional vertical visualization screen to the collaboration session with the touch-table and Shariing.

To present a more visual outline of the features, Table 32 presents a summary of the selected similarities and distinctions of 4D Collab Tool and 4D Lean Board, as two components for the direct interactions with the users during collaboration sessions.

Table 32 Summary of selected similarities and distinctions of 4D Collab Tool and 4D Lean Board

| | 4D Collab Navigation Tool | 4D Collab Decision Tool | 4D Lean Board |
|-------------------------------|---|--|--|
| Development type | | User experience/Front-end | |
| Development technology | Object oriented for Mac | Web-based | Web-based |
| Equipment | Touch-table | Touch-table, Shariing software | Touch-table, Vertical touchscreen, Shariing software |
| User Interactions | | Natural User Interactions | |
| Input data | 3D .dae Scheduling as 4D-object from 4D Collab Service | 3D as .ifc and scheduling from 4D Collab Service | 3D as .ifc from 4D Collab Service Scheduling from scheduling table template |
| Scheduling | Gantt chart | Gantt chart | Lean schedule levels of Last Planner System |
| AEC project phase | Pre-construction | Pre-construction | Design, Pre-construction, Construction |

Furthermore, Figure 100 illustrates the implementation scope of the prototypes in correlation with a progress phase of a design and construction project and highlights the expanded scope of potential use of 4D Lean Board.

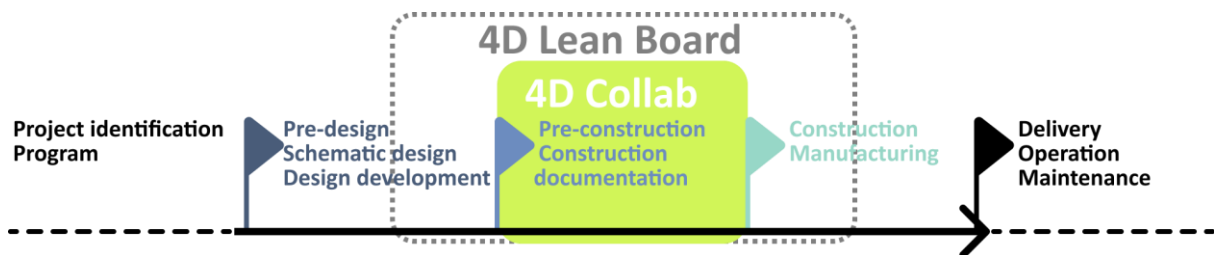


Figure 100 Implementation and use of 4D Collab Service and Tool, and of 4D Lean Board with the AEC project phases

5.1.1.2 Framework of 4D Lean Board prototyping

Design thinking and user-centered design approaches

In the context of prototyping, we developed a proposal of collaboration scenarios in correlation with the type of the project meeting (collaboration session), and the 4D Lean Board prototype as an interactive application to assist AEC professionals with decision-making during the sessions.

For the design and development of 4D Lean Board, we first relied on the Design thinking and UCD problem-solving methods to identify user needs and to design novel solutions. Secondly ***to generate and validate the design proposal***, and ***to explore the users' needs*** to provide a more effective proposal in the future.

Through the last decades different discourses have described ***Design thinking*** from the point of view of managers, designers, educators and academia (Johansson-Sköldberg et al., 2013). However, the important highlight of all the discourses is that the Design thinking implies ***an iterative and expansive design process***. In more detail, first, to explore the design problem the designers proceed with the ***information gathering*** to understand the future users and define their needs. Next, to ***explore the solution***, they gather future solutions ***ideas and emphasize them as a prototype***, which is finally ***evaluated*** by the users. In particular such iterative design is well suited for the early design phases and research prototyping, thus this is well suited for our research context.

Likewise, for the last three decades, there has been a development of design knowledge. Nowadays there are many approaches to design human-computer interactions (HCI) such as: ***User-centered design*** (Norman and Draper, 1986), or ***Usage-centered design*** (Constantine et al., 2003), or ***Goal-directed design*** (Cooper et al., 2012) or ***Human-centered Design and Activity-centered approach*** (Norman, 2013). In every approach the design is driven by different concerns.

According to Preece, the user-centered design implementation is based on an ***early focus on users and tasks, empirical measurement, and iterative cycles design*** (Preece et al., 2015). In our context, we focus on the primary users (architects, engineers, contractors, clients, etc.), who are understood as those who would have frequent use of the system during the meetings. The iterative cycle follows the similar to design thinking pass, and it repeats on every phase of the design development, and it includes: observation, idea generation, prototyping and evaluating

To implement it successfully, we should be “starting with a good understanding of people and the needs that the design is intended to meet” (Norman, 2013). Thus, the methodology stresses the importance of ***involving the real users through the development***, starting with the gathering of most relevant users' needs and requirements in order to develop the most appropriate. But further, it also highlights that is equally important to involve the users into the prototype evaluation (Preece et al., 2015), and to choose among alternative designs. Thus, we have run multiple user-tests as described further.

Prototyping team and agile management

4D Lean Board prototyping benefited from the expertise and inputs from different research team members. The core of three members of prototype development ensured: the ***user interface (UI) and user experience (UX) design*** together with the AEC professionals needs and the vision of a final product, evaluations design and production management (PhD student Veronika Bolshakova), the ***application architecture and web development*** (IT interns Antoine Roth and Clément Gérard). An extended prototyping team had also benefited from the ***expertise and supervision*** of research engineers

specialized in IT and Human Computer Interactions (HCI), and in Architecture (Pascal Humbert, Gilles Halin, Annie Guerriero).

According to Norman: “Great design requires a great management” (Norman, 2013). Thus, in addition to the implementation of UCD, the 4D Lean Board prototyping context created an opportunity for us to learn more about the coordination of a development team, and to understand and implement tools related to the application development. Therefore, the development team chose to manage the *prototyping with an agile set of practices*, which seemed to be rather well adapted for design experimentation and iteration for a continuous improvement following the *human-centered design* (Gabrysiak et al., 2011) (Al-Saqqa et al., 2020).

For the last two decades, Agile software development became common for application or web development projects (Brhel et al., 2015) (Al-Saqqa et al., 2020). Its implementation is also growing in many industries (Falkmer et al., 2001), and it tends to improve a product quality (Lallemand and Gronier, 2016b). Also, the Agile methodology has proved to be rather suitable for small and medium size projects (Al-Saqqa et al., 2020). Thus, it is well fitted for our prototyping context of quite limited time and resources, which yet seeks to explore several design hypothesis.

Even though, recently the term *Agile* is often used as a blanket term for many approaches (Falkmer et al., 2001), after being popularized with the Agile Manifesto (“Manifesto for Agile Software Development”), we use it as an approach that encourages the agile team to *focus on a rapid product development* in order to obtain *a rapid user-feedback* (Falkmer et al., 2001), and which supports design and development in *short iterations* (Brhel et al., 2015). Thus, with the help of the Agile our team fostered the prototyping collaboration as the management, communication and production, by enhancing social and digital engagements, and were rather efficient to manage the complexity of the development project tasks (see Figure 101).

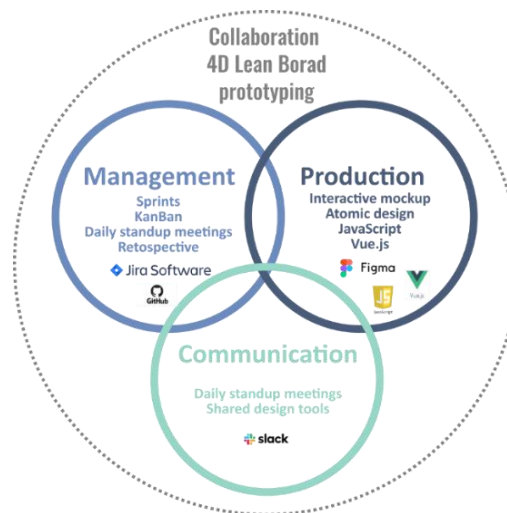


Figure 101 Schema of the collaboration aspects and tools for 4D Lean Board prototyping

In addition, since the Agile and Lean approach, even being focused on different results, they also stand on similar principles (focus on value, small batch sizes, elimination of waste (Falkmer et al., 2001) and spirit (Rodríguez et al., 2019). Hence, it was also particularly useful for the development team *to shift the mind towards the key features of these modern management approaches*, and therefore to understand and implement a better design of the lean planning.

In further details, for 4D Lean Board prototype management and communication the team followed *Scrum* framework values of transparency, inspection, and adaptation (Rodríguez et al., 2019), as the team implemented the practical tools of Scrum and Kanban (Scrumban (Falkmer et al., 2001)) for design and development, which are one of the most used nowadays (Al-Saqqa et al., 2020) (Dingsøyr et al., 2012). Even though our team size was rather small for such tool's major benefit they have proved to be nevertheless efficient and useful.

Sprint 1

- Hands-on development and draft version of the prototype
- Establishment of a plan and a workflow for design and development
- Technology and contents limitations evaluation
- Design proposal of 4D Lean Board v0.1

Sprint 2

- 4D connection and communication development for 3D data and scheduling data
- Integration of the 3D and scheduling visualization as a 4D into the same webpage
- Adjustment of design proposal of 4D Lean Board v0.2 with LPS task requirements integration
- Adjustment of a plan and a workflow for design and development

Sprint 3

- Visualization of the first version of the design of the Look-ahead schedule with the 4D simulation
- Implementation of simple touch interactions with 3D and scheduling information
- Design proposal of 4D Lean Board v0.3 with 3D filters and object selection
- Summary of v0 and adjustment of a plan and a workflow for design and development

Sprint 4

- User's workflow establishment for session data preparation
- Synchronisation of the 4D views for the users
- Design proposal of 4D Lean Board v1 with team filters and schedule levels
- User testing and adjustment of a plan and a workflow for design and development

Sprint 5

- Integration of the renewed design proposal and optimisation of interactions
- Design proposal of 4D Lean Board v2.1 with new tasks design and IFC filters
- User testing and adjustment of a plan and a workflow for design and development

Sprint 6

- Integration of the renewed design proposal and optimisation of interactions
- Design proposal of 4D Lean Board v2.2 with new tasks details and 3D styles
- Evaluation of the technology and skills limitation with the project progress retrospective
- User testing and adjustment of a plan and a workflow for design and development

Sprint 7

- Design proposal of 4D Lean Board v2.3 with detailed 3D filters and cameras position
- Optimisation of the prototype connection to the server
- IFC file information integration into the prototype
- User testing and design feedback for further adjustments

Sprint 8

- Design proposal of 4D Lean Board v3 with schedule adjustment option
- Re-evaluation and adjustments of the prototype architecture to the schedule modification option
- User testing and design feedback for further adjustments
- Prototyping summary

Figure 102 Summary of the main sprint aims for 4D Lean Board prototyping

Despite some particular design and development scheduling conditions (COVID-19 pandemic), the team managed to finish **8 sprints** of an approximate two-week duration each. Where the sprint is: “a time-box of one month or less during which a “Done”, useable, and potentially releasable product increment is created.” (Rodríguez et al., 2019). Figure 102 summarizes the sequence and the main goals of the 8 sprints to indicate a more comprehensive description of the prototyping’s scope and progress.

The sprint planning and progress tracking was held with the help of an online coordination platform “JIRA Software” by Atlassian which kept the backlog, the sprint’s **Kanban Board** and the epics,’ user stories’ and tasks’ lists. In addition, the team’s communication was supported with virtual and live **Daily Stand-Up** meetings, collaborative design and tests, and **sprint review and retrospective meetings**.

Design production

The alternative designs developed during the work on 4D Lean Board helped to explore a number of hypotheses and ideas. However, **the usability and technical feasibility together with experiments’ feedback** were guiding the design. In addition, the principles of design proposed by Norman were taken into consideration: **discoverability, feedback, conceptual model, affordances, signifiers, mappings and constraints** (Norman, 2013).

It is important to distinguish the frequently used terms of the design and HCI such as usability, utility, effectiveness and effectiveness. According to the description of Preece (Preece et al., 2015), a **usable application is easy to learn, effective and enjoyable to use**. Utility of application corresponds to the right functionalities for the user requirements.

Effectiveness of the application refers to how good is the result of the use of it, and efficiency on the other hand refers to how well it supports the actions for which it was designed. Also, according to Norman, an effective design must satisfy several constraints such as: **shape and form, cost and efficiency, reliability and effectiveness, understandability and usability, the pleasure of the appearance, the pride of ownership, and the joy of actual use** (see Figure 103) (Norman, 2013).

The production part of the collaborative prototyping is represented by the design, the web-development and the testing activities. Aside the low fidelity prototyping through sketching, we used an online design and interactions prototyping platform Figma⁶² for the high-fidelity prototyping. The platform offered the instruments for the 4D Lean Board **interface mockup within an illustration of the users’ interactions**. See an example of the interface and the mockup (see Figure 104).

The platform also offered to all the team members to share or to develop the designs together through a distant collaboration and through mockup annotations. In addition, together with the Figma UX/UI design tool we had an opportunity to implement the **atomic design methodology**. The methodology proposes to create scalable design systems based on 5 different levels of detail of the design elements (Frost, 2013) and their easy export to corresponding web components.

Therefore, it also fostered a more collaborative prototyping between design and development part of the team. For example, a change of design of a single elementary “atom” of design was automatically implemented to the whole mockup, containing the element. Another example is that the development part of the team found useful the feature for exporting the design elements directly into CSS code or image files of .png or .svg formats, which facilitated further integration.

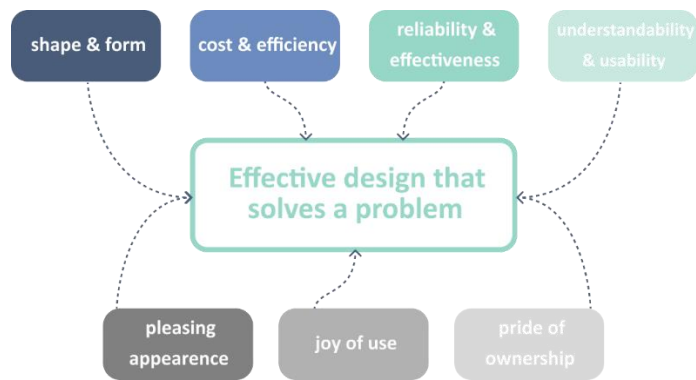


Figure 103 Effective design constraints

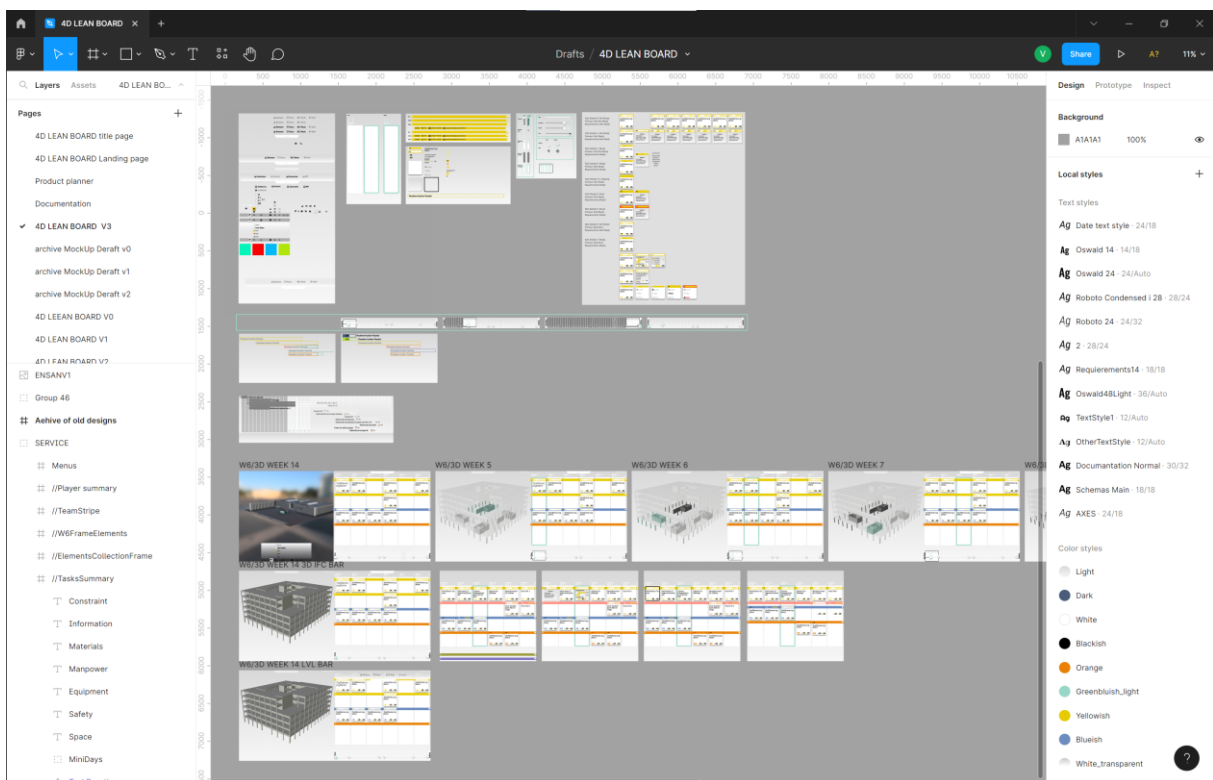


Figure 104 View of a 4D Lean Board mockup in Figma interface

Web-development production and functioning structure overview

The web-development tools were supporting the prototyping collaboration as well. For example, we used the common web development as Git⁶³ control system and GitHub⁶⁴ code repository (Chacon and Straub, 2014) to coordinate the work of two developers. With these tools we could track the code versions and assure a safe development of new features on separate sub-branches of code which were further integrated into the main branch with a possibility of an easy backup. MAP-CRAI webserver dedicated to the project hosts the 4D Lean Board application for the users.

HTML, CSS, JavaScript were used to build the 4D Lean Board interface in a browser, as the frontend part of the prototype. The Webpack⁶⁵ module was used to organize the code into separated assets within the development environment in order to have efficient and flexible data structure. It also

reassembled the assets (JavaScript and CSS files) together into a single file to be read by the application Vue.js as a “bundle.js.” In addition, **Babel**⁶⁶ compiler implementation into Webpack offered an access and possibility of integrating the newest JavaScript language features into the prototype development and their compatibility with the older language versions. Thus, the 4D Lean Board is compatible with most of the web-browsers and with node.js. **SCSS pre-compiler** simplified the creation and delivery of CSS files from the development environment to the browser.

Vue.js⁶⁷ framework was also used for the application 3D and planning views management in the web-browser and for a better integration of the interactive interface aspects of the 4D Lean Board. In addition, it is adapted for a single-page applications as our prototype. The prototype’s visualization of a 3D BIM model was developed within **Autodesk Forge framework**, which was an efficient solution for IFC files visualization, and also future connection to 4D Collab Service.

4D Lean Board was organized as a **system of services: HTTP, REST API, Interface synchronization**. The basic HTTP server build with Express framework shared the static files with the web-browser as well as send the application Vue.js to it. REST API⁶⁸ managed the data manipulation exchanges (such as planning updates as a JSON file) between the data server, web-socket and the web-browser without downloading the 4D model. The Interface synchronization server managed the real-time interface synchronization exchanges by using the web-socket technology which maintained the browser-server communication. Figure 105 summarizes the 4D Lean Board functioning structure. The system testing was run within unit testing, more precisely with JEST⁶⁹ JavaScript framework.

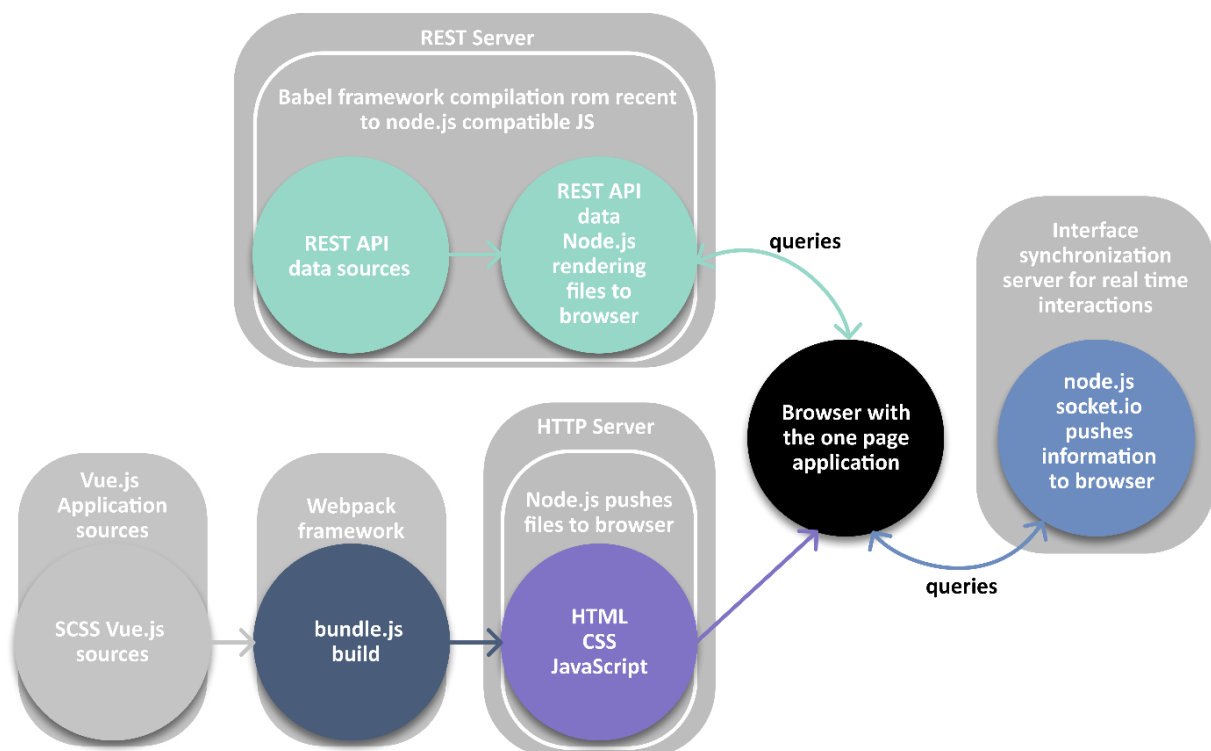


Figure 105 Diagram of 4D Lean Board functioning structure

5.1.2 Features of 4D Lean Board

This section first *summarizes the concepts* used to build the 4D Lean Board application architecture through an UML entity-association model in section 5.1.2.1. The purpose of the section is to layout the concept's relations and their role in the application and connection to the interface elements.

Second, this section highlights that the prototype's interface design was challenged by a complexity encompassing the requirement for *multi-user interactions* and the *requirement for visualization of multiple levels* of project information. Additional complexity is also brought by two possible workspace settings, which are comprising either only a touch table as a support, or a setting with a vertical screen and the touch table. The following subsections describe *the user interface* of the 4D Lean Board starting with the elements of the 3D view (5.1.2.3) and then of the Schedule view (5.1.2.4).

5.1.2.1 Model of 4D Lean Board concepts

Purpose of the model

In order to provide a better overview of the prototype, we summarize the application concepts through a conceptual modeling with an UML (Unified Modeling Language) class diagram which illustrates *the main concepts and their relations used for the prototyping*. This model presents the concepts that further also may be found as the 4D Lean Board interface or application architecture elements.

The presented UML model is conceptual and not the implementation model, since the main purpose of this part is to describe the application elements and concepts and not to go further into the application's development details. However, during the development the implementation diagram was used as well to build the architecture of the application. The architecture is built in a way to allow the Agile development by sprints of the Schedule levels and to separate the queries.

Elements of the model

The UML model (Figure 106) illustrates that there is "*Construction project*" concept that contains information about the project details and sets the goals of the start and end date, records the progress, sets the workdays and holidays. During the preparation part such information comes from the schedule table in our case, with the dedicated column that lists the holidays and workdays. This concept is also connected to the classes which are representing the levels of schedule corresponding to the schedule levels views (Milestone View, Phases View, 6 Weeks View, Week View) on the application interface. Their addition to the model is not necessary from the application architecture point of view but is practical for the application concepts description.

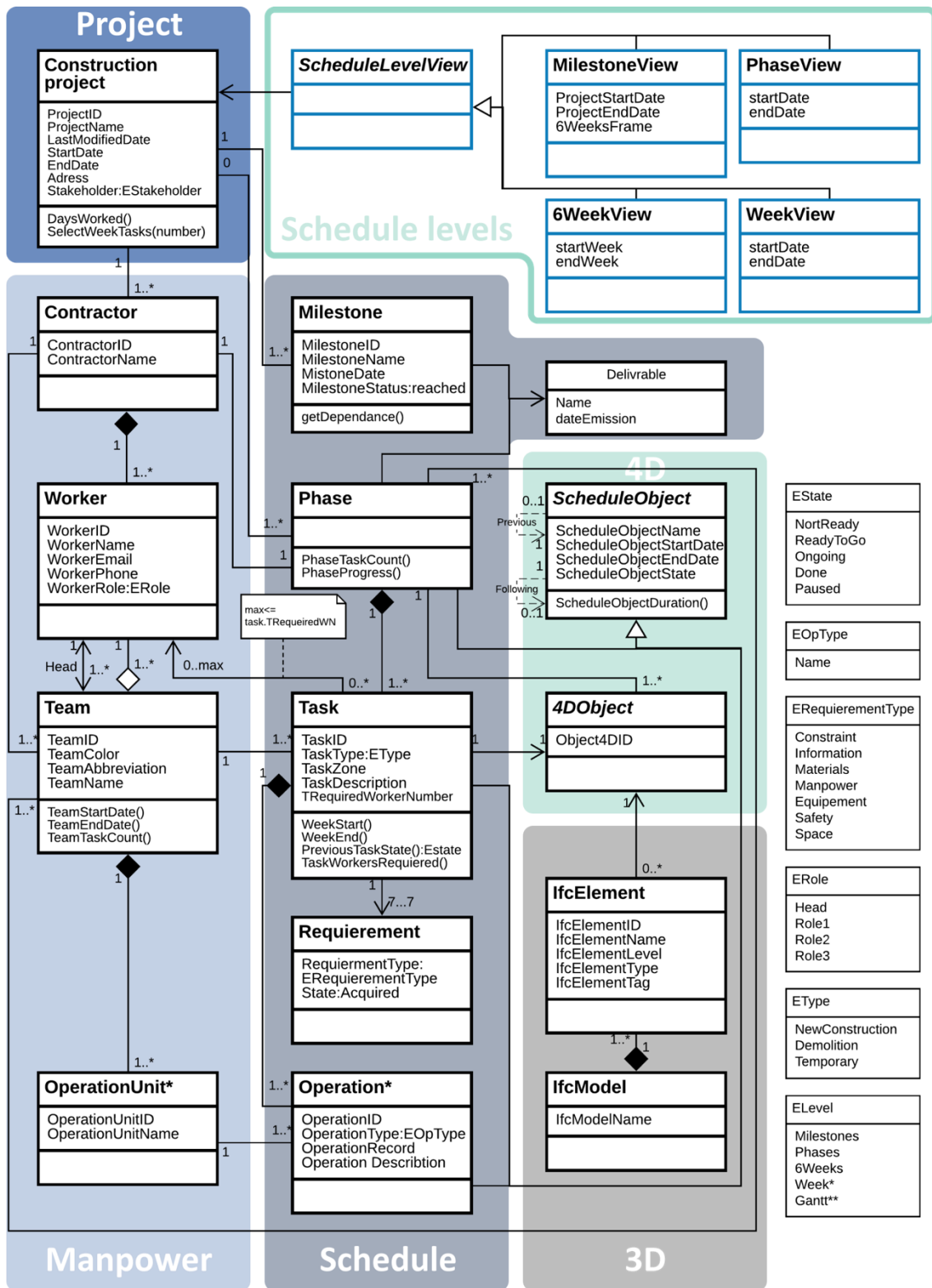


Figure 106 Conceptual UML model of the 4D Lean Board key elements

The classes "Milestone, Phase, Task" and "Operation" correspond to the key elements of the Schedule level views Milestones, Phases, 6 Weeks and Week. The main purpose of the "Milestone" is to indicate the date on the project calendar and to keep track of the completed milestones. The "Phase" class has more complex relations within the model, and it naturally corresponds to the phase on the interface. The "Task" class corresponds to the sticky note element of the interface. The Phase and the

Tasks are related to an abstract class “*Schedule object*” that manages updates and adjustments. They are also related to an abstract class “*4DObject*” whose main purpose is to create the 4D link between the Tasks (and by composition the Phases) and the “*IfcElements*” of the “*IfcModels*”, and provide the 4D Lean Board the necessary information for 4D filters. To initially create the *4D link* the application needs *a schedule table (.csv preset template) and IFC 3D models*. The schedule contains a column with the IfcElements IDs and the related tasks.

Another important aspect of the application is the management of the workforce related to the construction tasks. Thus, the project is related to a “*Contractor*” class, naturally a project may have many related contractors. The contractors have Teams composed of the workers; the team corresponds to the color band on our schedule interface. The same team color also appears on the 4D view filters “by Teams” (Figure 114). Every team has a team head, who would manage the updates and assign the workers to the tasks.

Limitations

Our limitation was that one task may have zero or many IfcElements. An IfcElement may be attached only to one task. This limitation was accepted in order to provide a quicker development and thus explore the user interface features and collaboration details.

Also, the Operations concept which corresponds to the Schedule level “Week” is included into the model in order to manage all the required details, however on the user interface side this schedule level is not implemented due to the development time limits and priorities. However, in the future the implementation into the UI is possible without modifications of the application’s architecture.

5.1.2.2 Multiuser interactions and separated synchronized views

With technology we can foster users’ interactions with applications and increase benefits from collaboration. However, Norman points to a paradox that even with certain benefits the added complexities from technology may increase user frustration or add unnecessarily difficulties to their work (Norman, 2013). Therefore, the designers must be aware of such possibility.

The development context for a co-located synchronous collaboration implied that the prototype’s interface will be adapted for *multi-user interactions*. Even though the sharable interfaces provide more opportunities for collaboration, the multiuser interactions add a certain complexity to the design and prototyping tasks by raising the question of *mutual awareness* about the Digital collaboration workspace, which is described by Preece as: “being aware of what is happening around you in order to understand how information, events, and your own actions will affect ongoing and future events” (Preece et al., 2015). In addition, the constraints of *mutual control and mutual availability* must be taken into account during the prototype design as well (Yuill and Rogers, 2012).

Since the prototype is designed to be used during a collaboration session on the touch table, which is supporting natural fingertip interactions, the users may simply observe the interactions made by other users. Thus, the *touch-interface* itself already raises the mutual awareness and more equitable participation (Preece et al., 2015). In addition, by focusing on natural user interactions implementation for the prototype interface design, we also raise the information availability and the ease of control. We tried to design an interface that fosters “learning” as an aspect that encourages users to exploration.

Even though the 4D Lean Board is rather described as a single page web-application, the possibility to *separate the “3D view” and “Schedule view”* is the core feature of the prototype. Another core feature referred to as *synchronized views* keeps a continuous link between 3D and schedule view’s

copies. Therefore, the users may customize a layout of their collaboration workspace according to their needs.

For example, two users sitting on the same side of the table may be sharing the 3D view, but each one may have a separate schedule view. Also, due to the separation of the views, not only the tabletop workspace can be customized, but the vertical screen layout may be adjusted to the collaboration session needs as well. For example, the users may choose to visualize the 3D on the vertical screen in order to enhance a project details visibility, but use the small version of the 3D on the table as an interaction interface without a need to go to the vertical screen. Figure 107 summarizes a schema of possible layouts examples.

Following the separated views, to foster the awareness with explicit feedback the 4D Lean Board interface indicates to the users when the *4D simulation is played* in *4D visualization mode* through the common color scheme with the highlight color and frame. Further, *when switching to Schedule adjustment mode* users receive feedback from the interface through a temporary suspension of interactions and by adding a *highlight frame* to all the views.

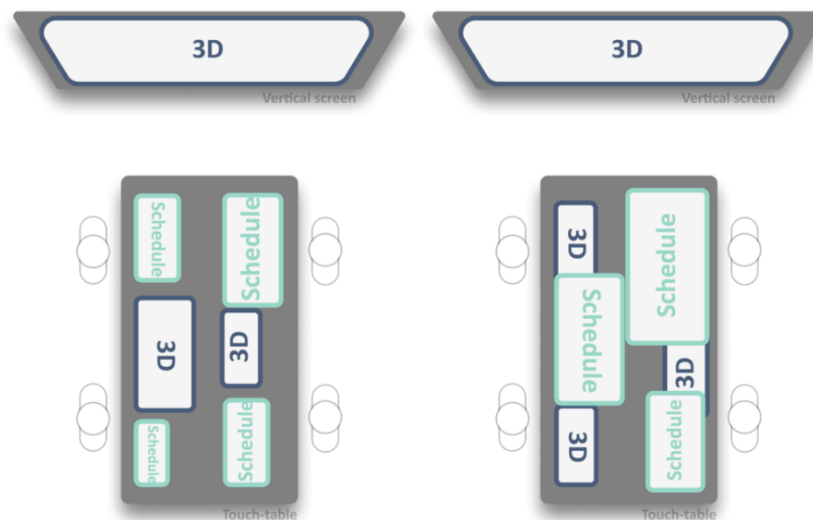


Figure 107 Schema of the 3D and scheduling views possible layout on the touch-table

5.1.2.3 3D view features and elements summary

Basic features

Naturally, the main purpose of the *3D view is visualization* (display) of the 3D BIM model of a project. In other words, it must first basically provide the users with a clear image of a project. So, the maximum of the 3D view space is dedicated to this purpose.

Following the visualization, simple touch interactions with the 3D BIM model provide the users with the virtual environment navigation. Nowadays the majority of users are *familiar with simple interactions such as move, pinch, zoom* due to broad use of smartphones and tablets for project visualization and follow ups. Naturally, we implement those into the interface.

In addition to the navigation with the touch gestures in the area of a 3D model virtual environment, the design offers a user an additional tool: *3D navigation cube*. It helps to switch the camera position swiftly or to reset the view. The navigation cube, being in our case a part of Autodesk Forge 3D viewer

features, is a broadly used tool concept in modeling software. Thus, its implementation into the prototype interface aligns the interactions with current AEC practices. Figure 108 illustrates the 3D view interface layout and highlights the interaction tools.

The second important purpose of the view is to provide an access to BIM information of the 3D model elements and to provide users with the most relevant information about the project. This feature is already broadly implemented in BIM viewer software solutions and common practices. To access the BIM information, the user makes a simple touch click on a 3D element and may see the *information in the properties view* (Figure 109).

However, the design challenge is also to efficiently display the 4D link of a selected 3D model element to the schedule. In order to do so, the 3D view provides *a zoom in on the selected element and highlights it* (green color), so the user's focus is entirely on the selected element. The schedule task related to the selected element is highlighted as well in the schedule view. The selection of a task ("press" interaction) also leads to a selection of a related 3D model element. Figure 109 illustrates the 3D view and scheduling highlights of the selected 3D element. The functions of 3D section and IFC model hierarchy visualization complete the 3D view interface (Figure 110).

3D and 4D filters

A possibility to customize the 3D view information and the 4D link highlight according to the user's needs and the aim of the discussion is essential for efficient collaboration. Thus, the 3D view interface provides users with 3D view filters and 4D link filters.

The first filter from the top slide bar menu hides and unhides the 3D elements from the view by their IFC file origin, thus *filters by "IFC file"*. Such a filter is common in BIM viewers nowadays, and it has proved to be useful when visualizing the 3D BIM models issued by different authors. Figure 111 illustrates a summary of the top slide bar design and an example of a configuration of IFC file filter, with the 3D models from architecture, structure (hidden), construction and MEP (hidden).

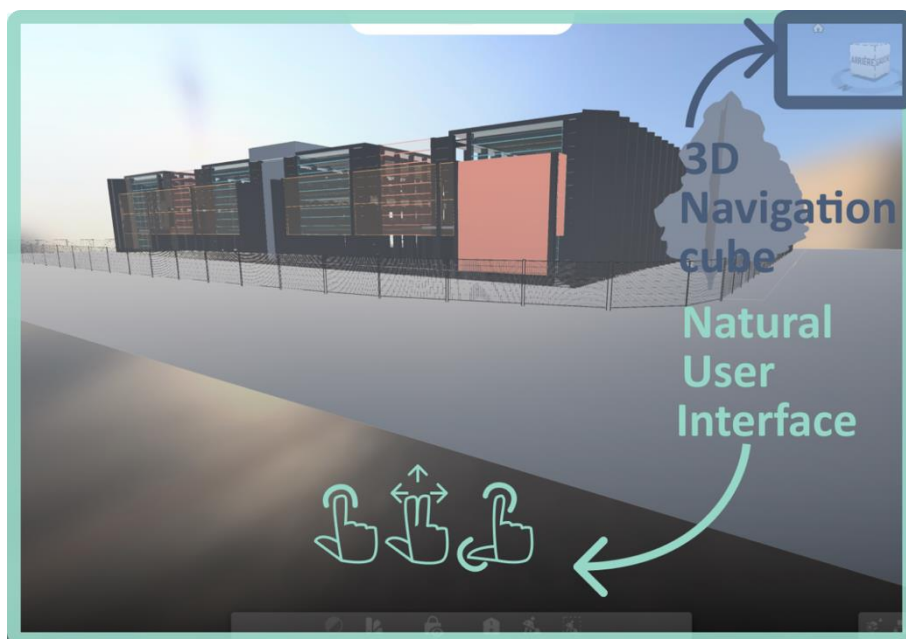


Figure 108 Basic features of 3D view: interaction tools

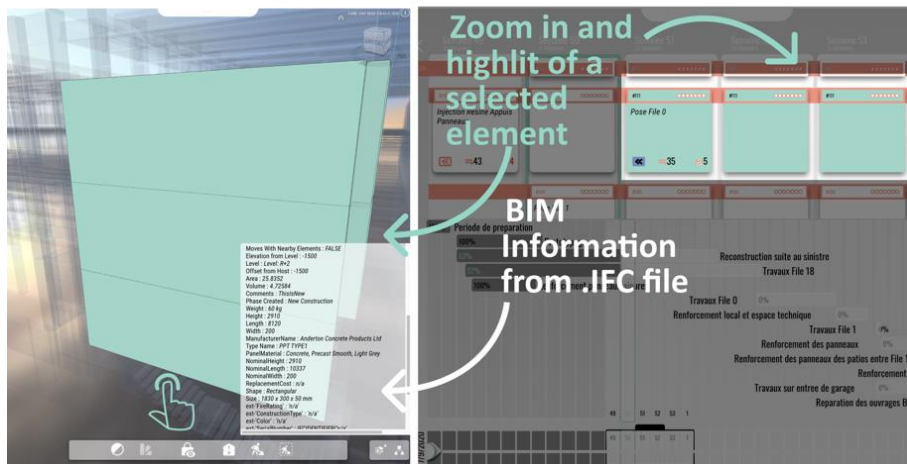


Figure 109 3D view selection of a BIM model element with zoom in and highlight of the element and proprieties

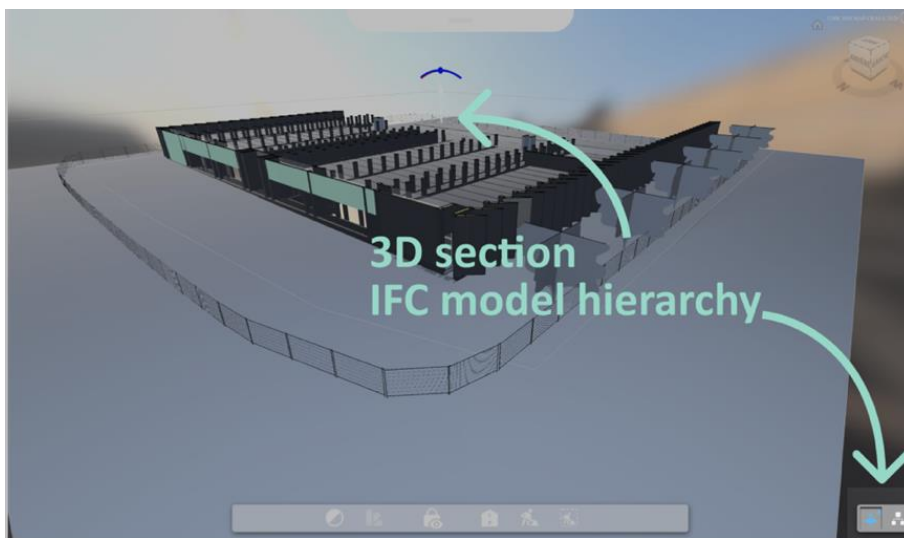


Figure 110 3D section and file hierarchy access buttons

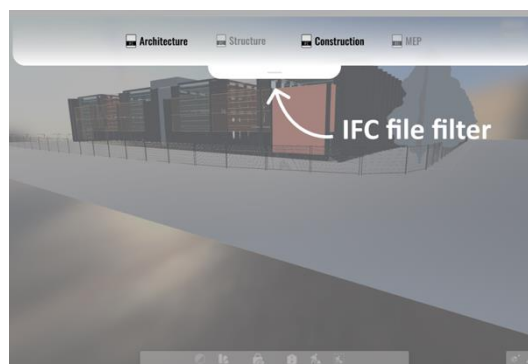


Figure 111 3D filter by "IFC file" menu summary

The filter bar on the bottom of the 3D view unites the 4D filters, the camera position lock button and 3D filters. The Figure 112 illustrates the elements of the filters bar. The 3D filter's first button offers to hide or unhide the elements of the model *by building level*. This filter offers a better view of every level

without needing to use a 3D section. The next button is filter by *construction type*, such as temporary, demolition, new construction, existing. This feature offers also clearer visibility on the types of construction works and thus highlights them for a better understanding of the project. The last button offers a filter *by construction zone*, which hides and unhides the elements of the model by their construction zone predefined in the schedule (Figure 112).

The 4D filters offer two 3D visualization style modes: *basic mode and teams mode*. The basic mode highlights the connected to the schedule elements of the 3D model in green color, the elements for the schedule of the 6 weeks to come are highlighted in white, the elements to come further are transparent with white edges, and the finished elements take their real material (Figure 113). This mode rather highlights the elements of the model and the sequence of the works to come. Yet, it is rather suited for the project overview during design and preconstruction.

On the other hand, the teams mode is better suited for a review or follow ups at reconstruction and construction. The teams mode highlights the elements of the 3D model linked to the ongoing schedule tasks with green edges and fills it with the color of the construction crew (or subcontractor) in charge (Figure 114). The 3D model elements connected to the tasks in six weeks to come are simply filled with the teams' color, and likewise the basic mode the elements to come in the future are transparent with colored edges, and the already built elements are colored with lower opacity.

As the test project we chose reconstruction type of project aiming to repair consequences of a wall collapse, and not a new construction, which would augment the complexity of research for efficient 3D visualization styles. The 3D visualization style changed the appearance of 3D model elements depending on the 4D simulation cursor position on the project timeline, and on the task type. Moreover, the distinction between the 'existing' elements and the elements of the project was necessary as well.

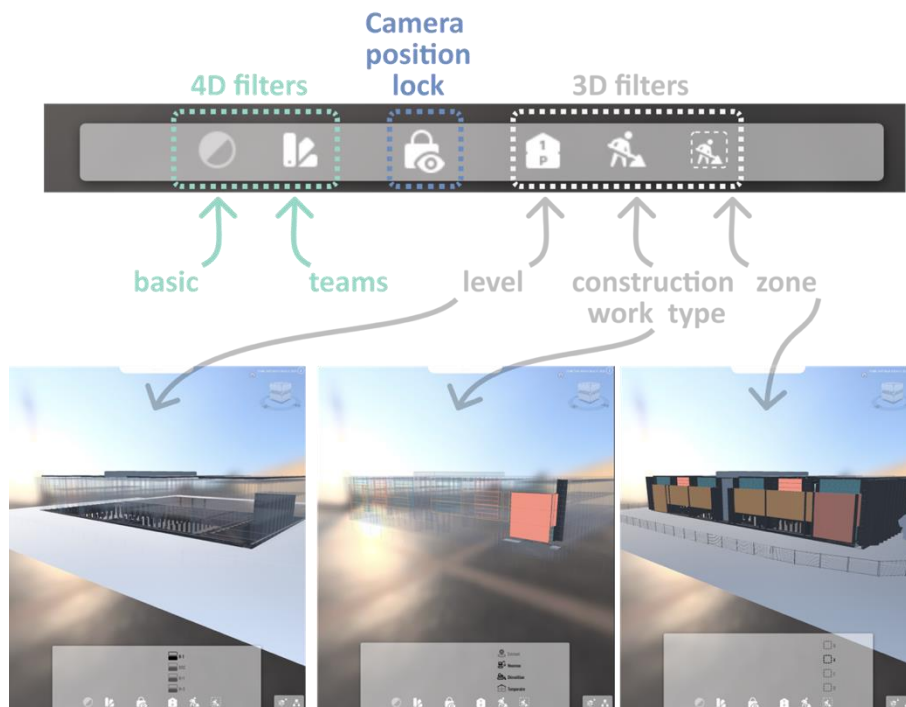


Figure 112 Filter bar elements: 4D filters basic and teams; camera position lock; 3D filters by level, construction work type, zone

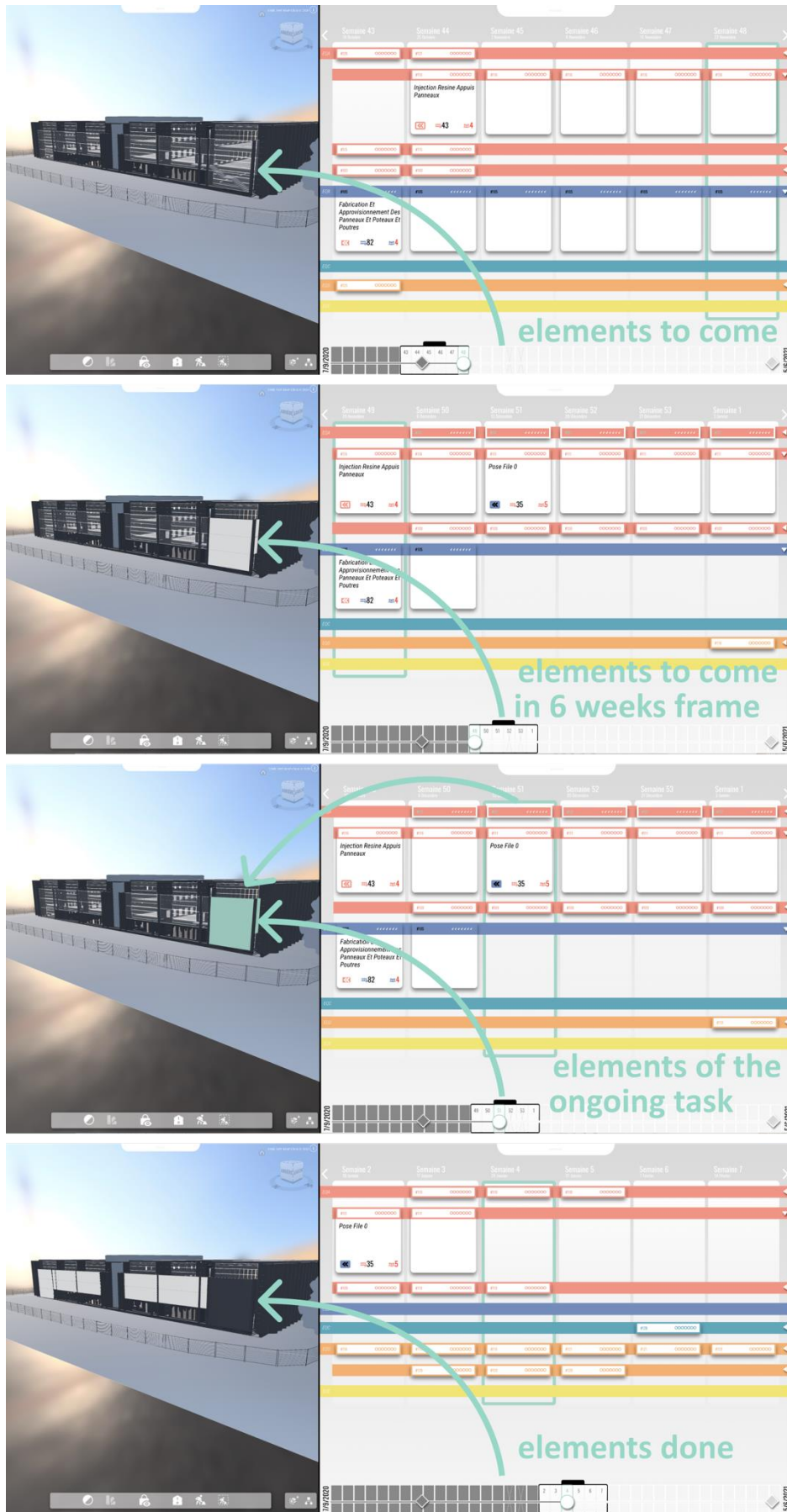


Figure 113 4D filter basic mode illustration: left 3D view, right Look-ahead 6 weeks schedule view

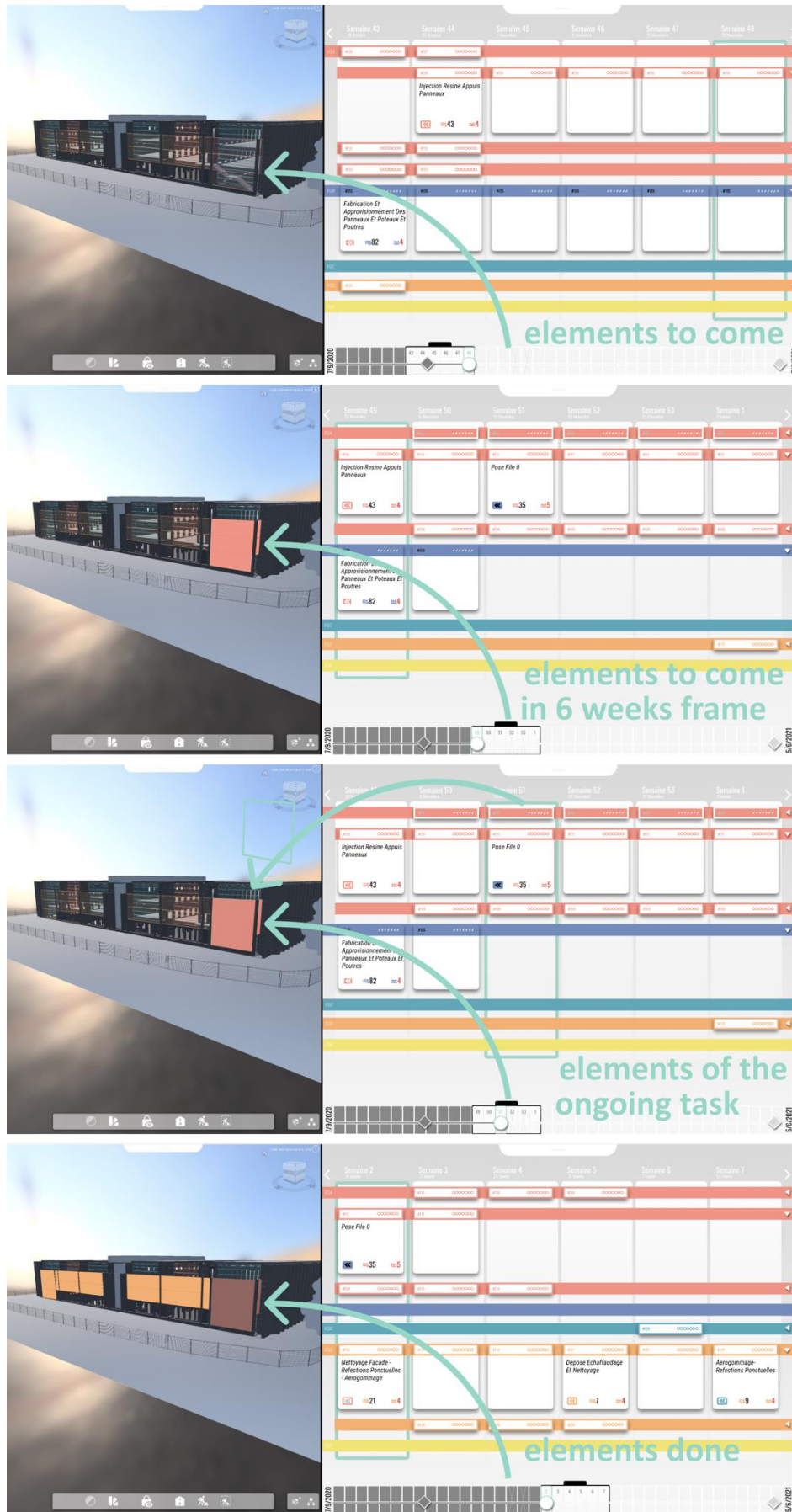


Figure 114 4D filter teams mode illustration

5.1.2.4 Schedule view features and elements summary

The schedule view provides the prototype users with *visualization, interactions and adjustment* of the schedule information. Also, through the schedule view's time cursor advancement the users run the 4D simulation. The schedule view offers a possibility to access *different levels of detail of the schedule*, in correlation with the project progress or collaboration type and needs. The levels of detail correspond to the Last Planner System schedule levels of detail (Figure 13, p.64). Such a flexibility of the schedule information representation offers a better adaptation of the prototype to that collaboration needs.

Thus, users may activate *milestones frame, phases frame, 6 weeks look ahead frame* schedule visualization through the schedule level of detail bar (Figure 115). The weekly workplan is considered in the development schema but was not implemented due to limitations of the prototyping resources and time. Even though the main focus of our prototyping is on Lean schedule information representation methods, users found it very reassuring and useful to also have access to a Gantt chart of the project. Through the top schedule level of detail bar users may activate the above-mentioned modes. The users may choose which schedule frame to display, and even may display all the frames in separate windows on the table and still benefit from the continuous 4D link.

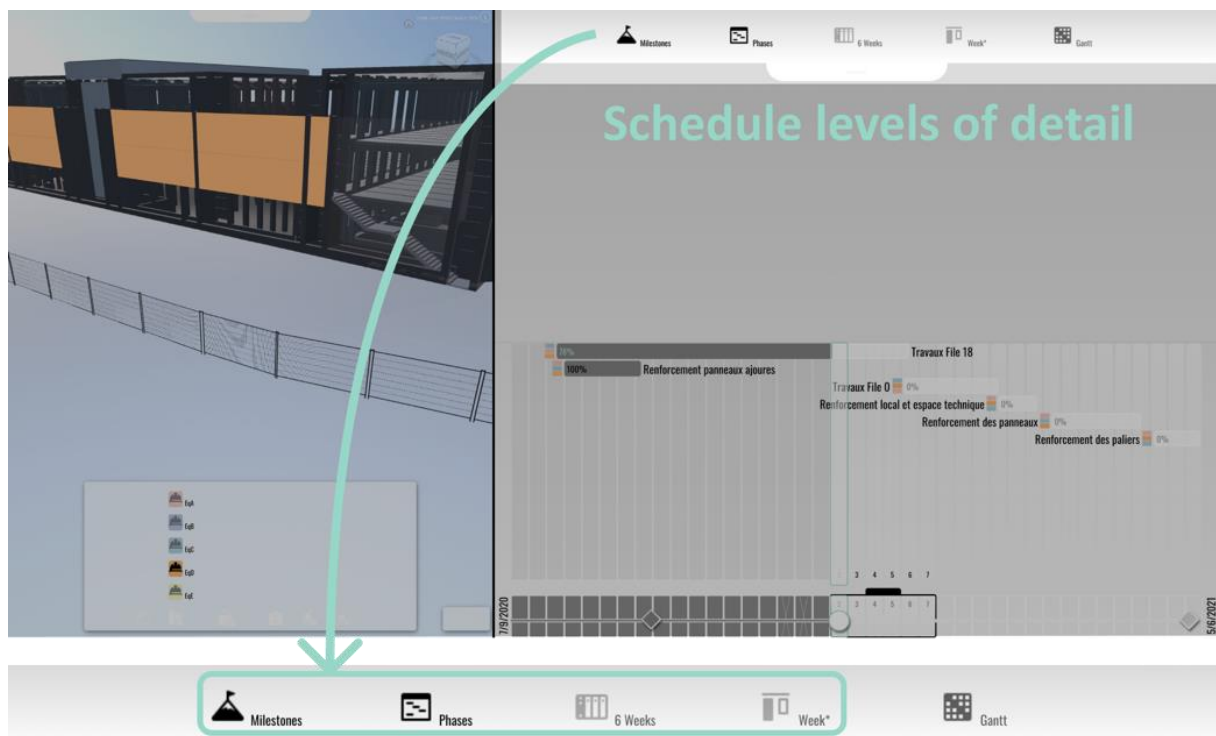


Figure 115 Summary of Schedule levels of detail bar

Milestones level and Phases level frames

The graphical presentation of timeline may be not the same depending on the cultural context (Norman, 2013), for example it may be read in vertical or horizontal, with the different representations of time past and the present. However, our prototype in European context for AEC professionals used to Gantt charts read from the left to the right, thus the timeline is horizontal with the past on the left. Also to improve the understanding of the interface, every level of detail of the schedule is based on a metaphor, which are widely used in interface design (Preece et al., 2015).

The milestones frame resembles a player with the start and end dates, the progress bar and the time cursor. A project week was chosen as the time unit for the 4D simulation play. It gives an additional scale to the project progress, and it correlates with the 6 weeks look ahead schedule frame. The six weeks frame also correlates with the look-ahead schedule. The milestone buttons from their progress bar offer the information about project milestones on press (Figure 116).

The phases frame has some resemblance to a waterfall chart with the project phases as main elements. The frame naturally offers a possibility to play the 4D simulation with the time cursor and the frame keeps the project week as a unit element to scale the project progress (Figure 117). It follows the same visual style as the milestones frame and the 3D view with either basic mode (Figure 117) or the 4D teams' mode (Figure 118). In addition, the user may access the basic phase information (Figure 119) and on selection it highlights the corresponding 3D model elements (Figure 120).

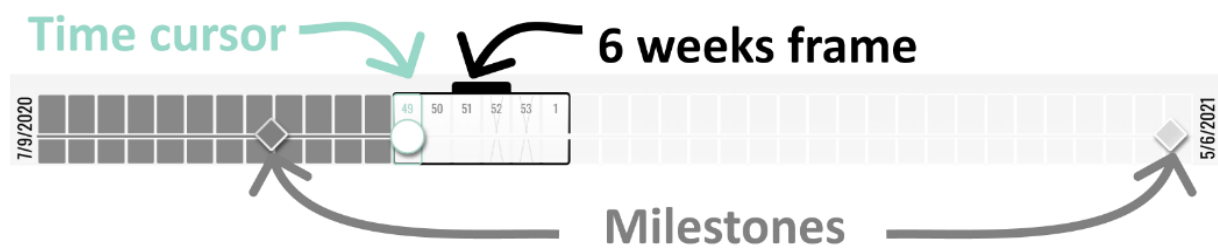


Figure 116 Schedule level of detail: milestones frame elements

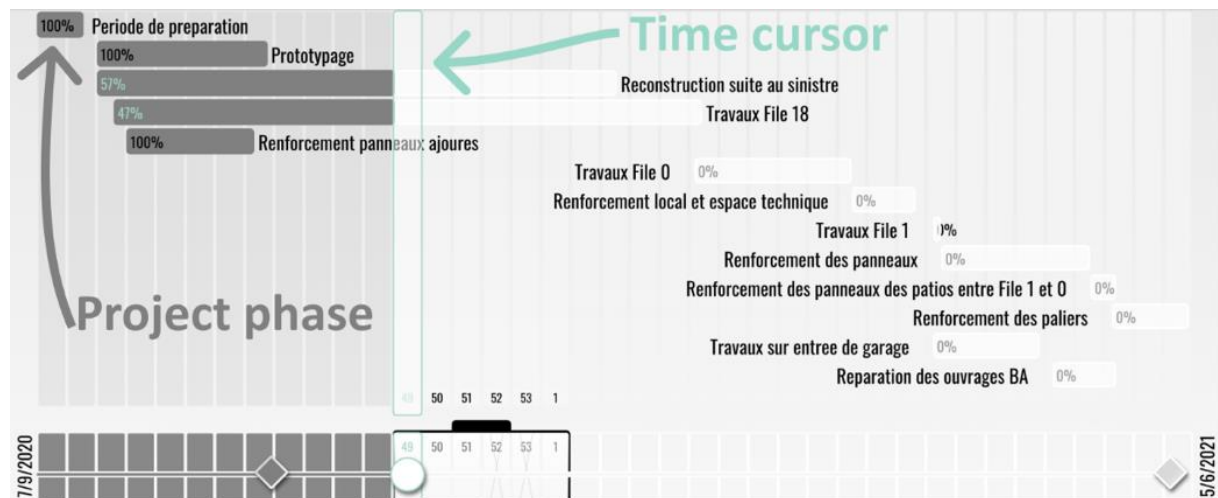


Figure 117 Schedule level of detail: phases frame elements

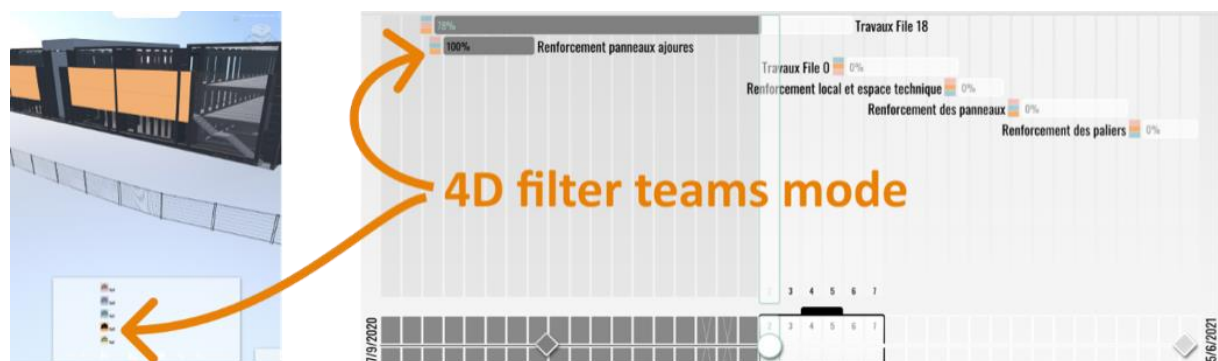


Figure 118 Schedule level of detail: phases frame with 4D filter teams mode

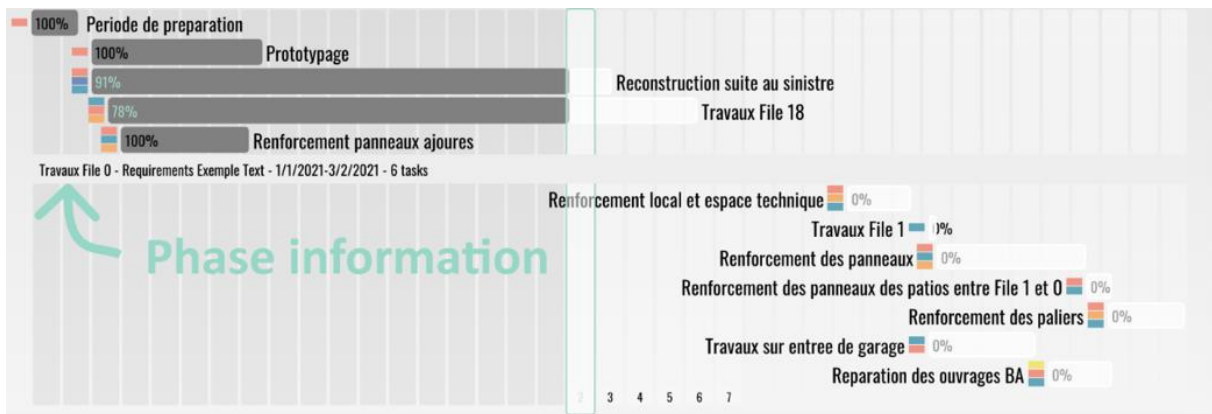


Figure 119 Basic phase information



Figure 120 Phase selection and zoom on linked 3D elements

Look ahead schedule frame

The next frame is the most complex one offered by the schedule view, and it represents the look ahead schedule. The prototype currently displays the 6 weeks look-ahead schedule, but there is a possibility to extend or shorten the weeks frame to adapt better to the particular planning requirements. The virtual 'sticky notes' represent the project tasks on a virtual dashboard. The 4D time cursor indicates the link of the schedule with the 3D. The user gets an overview of the tasks for 6 weeks to come placed on the colored stripes. The color of the stripe corresponds to either a contractor or a contractor's construction team depending on the project type and management (Figure 121).

All the sticky notes of the same color are attached to the same construction team. And when the 4D filter by team is activated for the construction team, the look-ahead frame is adapted as well. For example, Figure 122 illustrates the interface look and feel with the 4D filter by team active for Team A, thus the schedule displays only the tasks attached to the selected team. Naturally such an application of the filter is best suited for the team's tasks review and control. Also, the users may activate the filter for a few teams or all the teams. On task selection the attached 3D elements are highlighted as well (Figure 123).

Also, to obtain a clearer view, to save screen space and to summarize already finished tasks, the users may fold or unfold the team stripe to either have more details about the tasks, or to work with the task dependencies (Figure 124).

The task sticky note is comprised of two elements: the header and the body. The header displays the *task ID number and the task status, the status of the requirements*. The body displays the task short name, the task duration, the number of workers required for the construction tasks, and the previous task status and link. Figure 125 illustrates the task sticky note main elements.

The header not only displays the task ID and requirements, but also offers the users a possibility to either check the requirements state, and then change the task status to launched, done or paused. Figure 126 illustrates the task status change interaction in the header.

The design of the header is thought in a way *to indicate the task status even when the team stripe is folded*. When every task of the stripe is done it is fully filled. Figure 127 illustrates the progress from the task not ready to start with the requirements not filled, to the task 'ready to launch', 'launched', 'done' or 'paused'. Even though additional statuses would provide the users with more details and better control of the construction process when using the board, we *have restricted our prototyping to these three statuses* (Figure 127).

The requirements correspond to the necessary elements assuring task readiness and procurement within the process of the waste control: *constraint (conditions), information, manpower, materials, equipment, safety, space*.

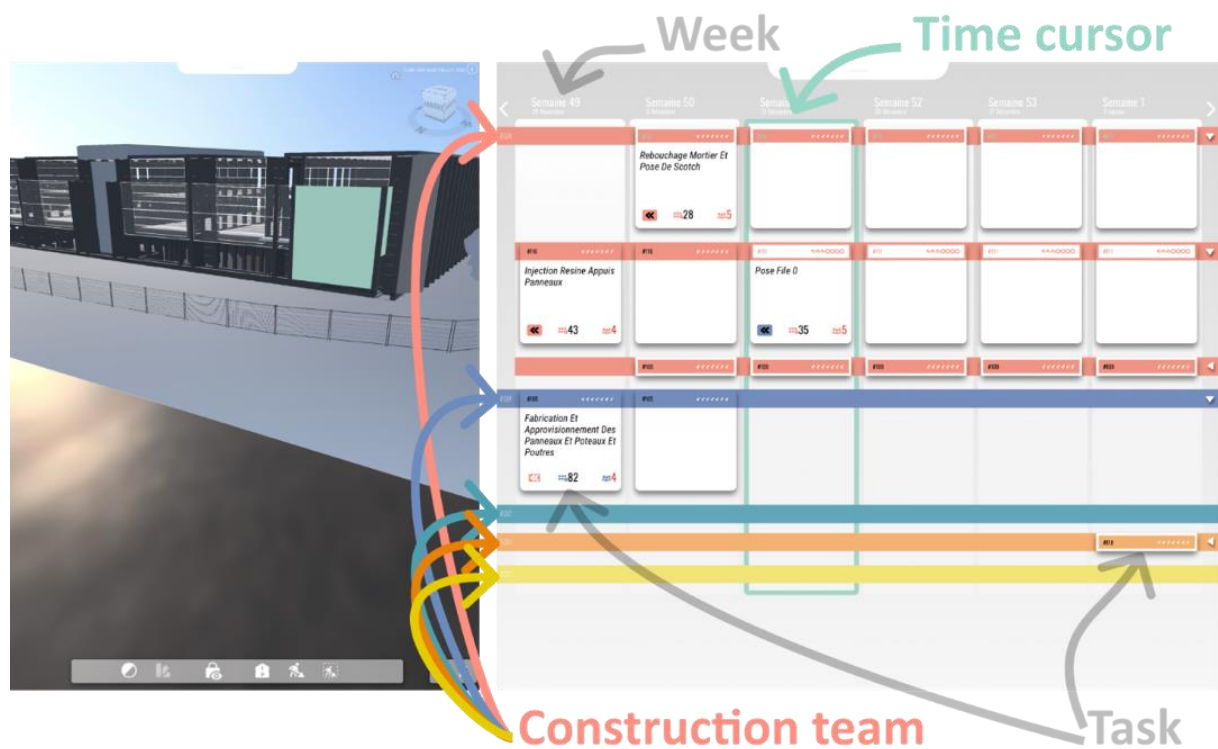


Figure 121 6 weeks look ahead board elements overview

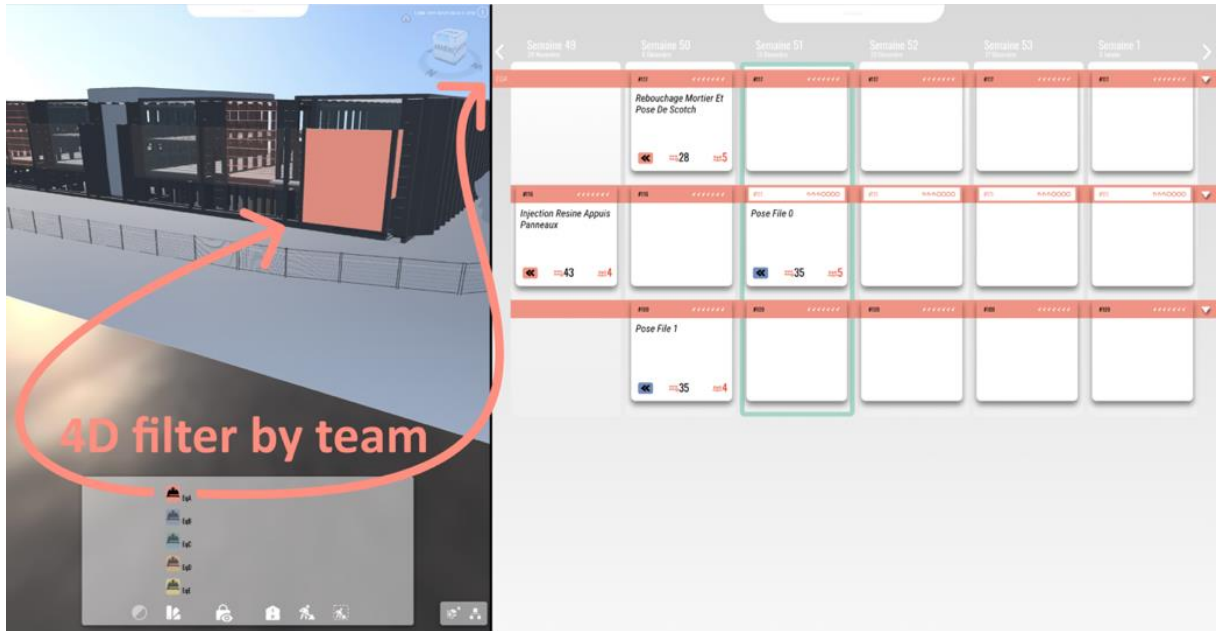


Figure 122 Look ahead schedule frame with 4D filter by team applied

Highlight of connected elements on selection

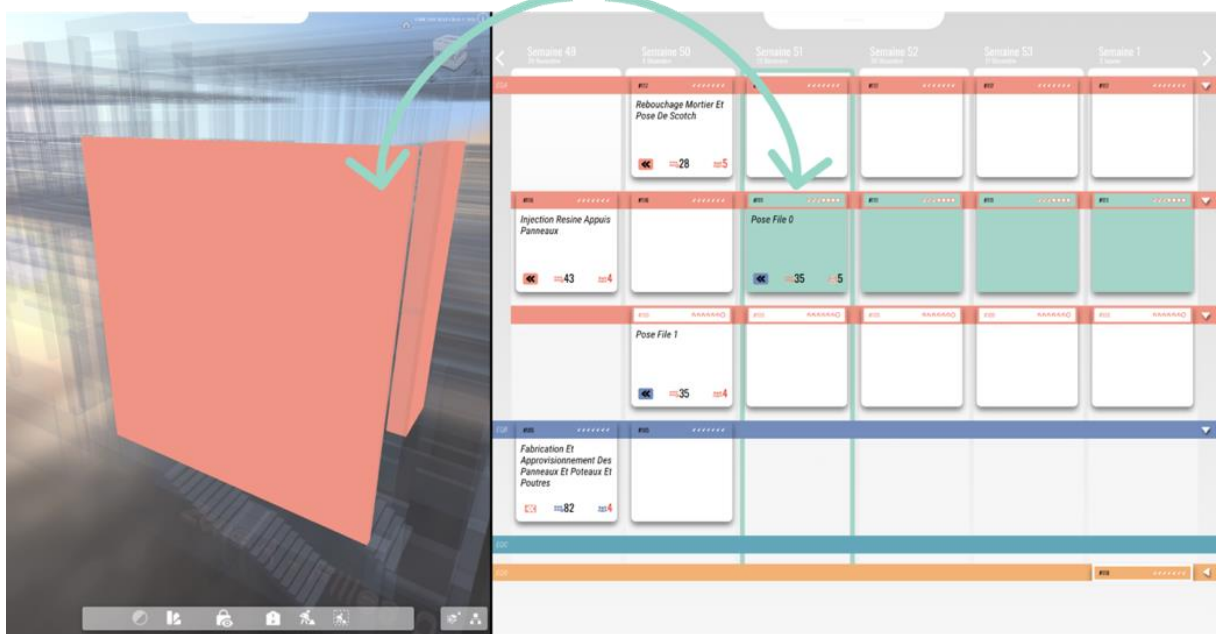


Figure 123 Look-ahead frame: 4D link highlight on task selection



Figure 124 Look ahead schedule frame elements: folded and unfolded team stripes

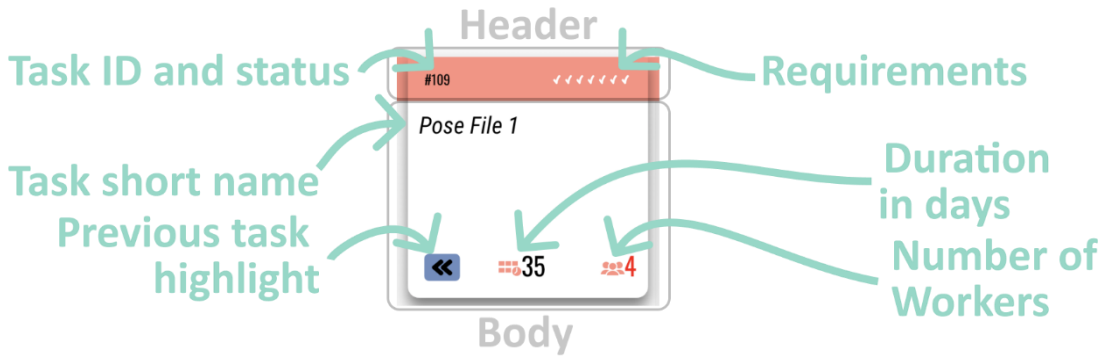


Figure 125 Task sticky note elements

Task status change

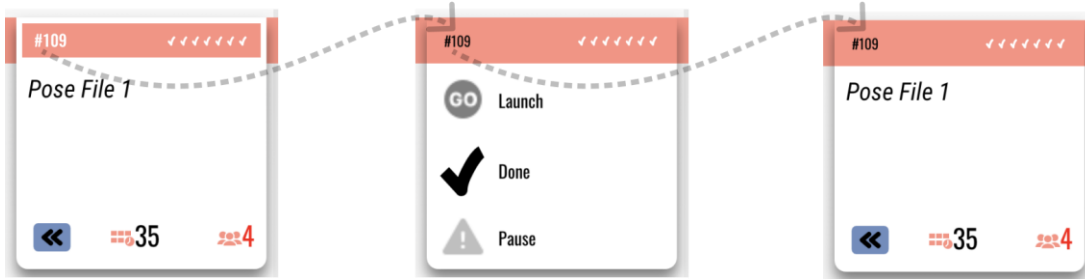


Figure 126 Task status change interaction schema

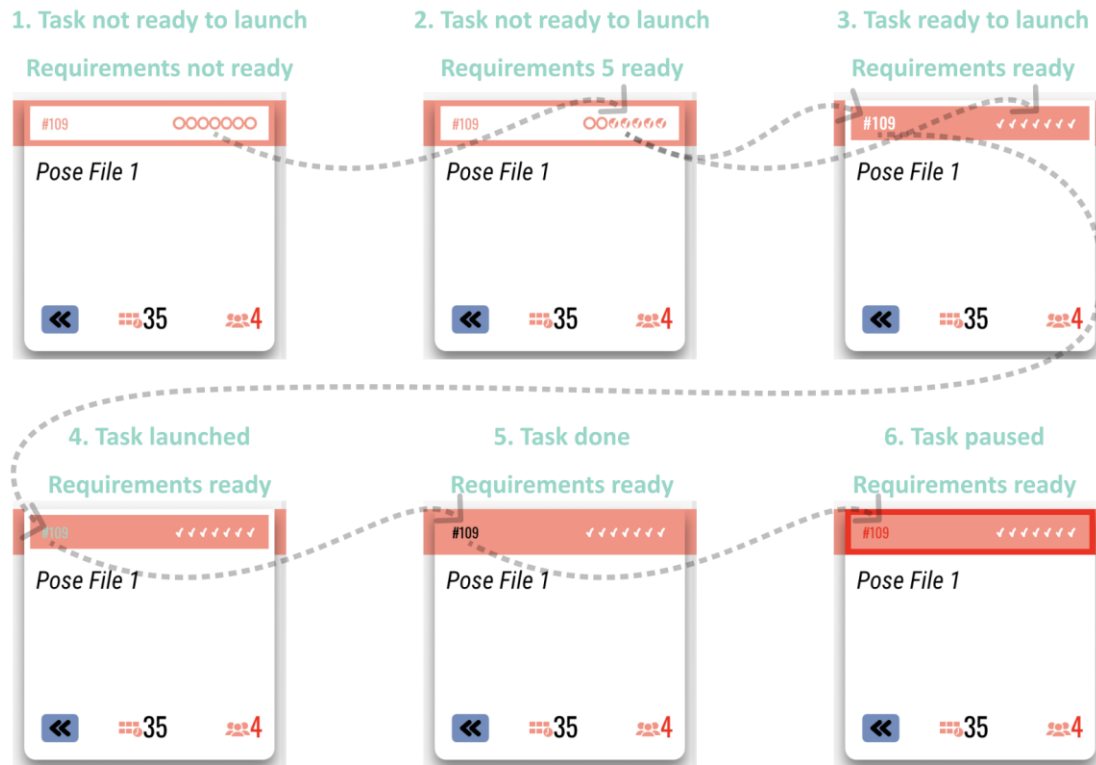


Figure 127 Task status summary

The task body not only displays the basic information about the task, but also offers additional levels of detail on ‘tap interaction’ on the sticky note element. It is important for users to conduct an activity effectively. The interaction design suggests avoiding information overload on the interface and therefore to add hidden levels of information with an easy access for users (Preece et al., 2015). The “less is more” in the interface approach also fosters decision-making since the human mind is designed to react quickly.

The users may first access task details: long task name, description, zone, level, type. They also have access to the task duration displayed on a calendar and a possibility to move the start and the end dates. The assignment list offers to a team head to assign the necessary and available personnel to the task, and also to verify if there is enough manpower for the task. Figure 128 illustrates the additional levels of detail of the task sticky note.

The other element of the task body is the button that highlights the previous task on press interaction, and it also indicates the task status following the same indications as the header task status. Figure 129 illustrates the task 109 from the red team connection to task 105 from the blue team and the indications about the previous task status.

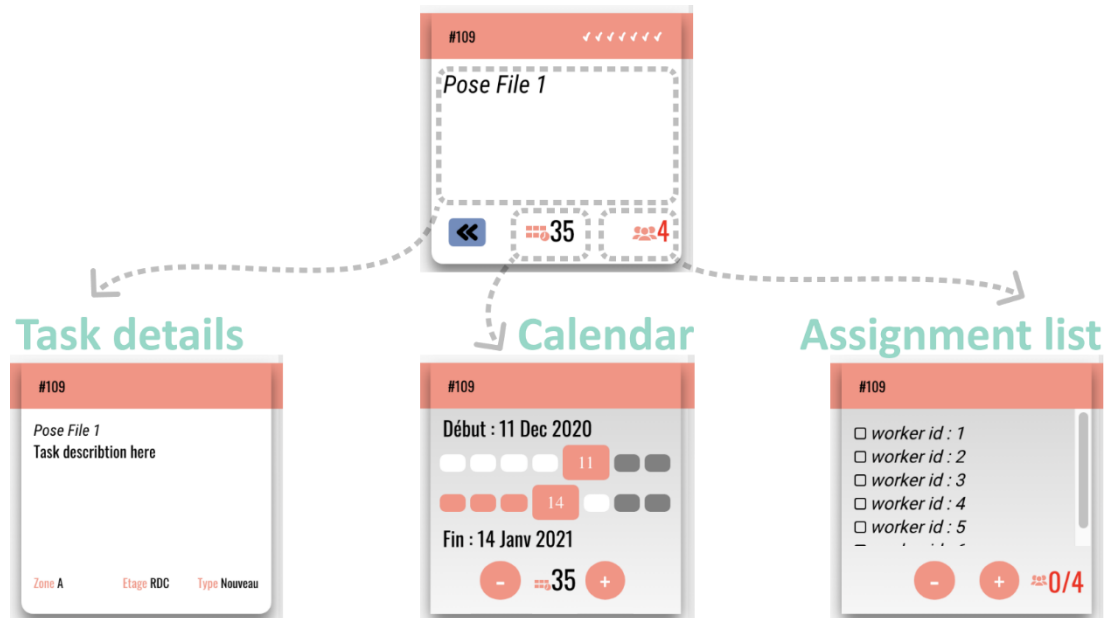


Figure 128 Task body elements: task details, Calendar and assignment list



Figure 129 Previous task status indication and link

Collaboration session and workflow

Providing the users with the *relevant project information visualization* for discussion and decision-making at the project meeting (synchronous collaboration session) was in our primary scope research. However, naturally many professionals work on design and construction documents using their specific professional tools, remotely and separately, but must bring the relevant project information to the meeting. This information becomes *an input data* for the meeting and after users may annotate the input data documents or create new ones, and therefore generate an *output data*.

Since BIM practices became a part of the common methods of design and development of construction projects, *the workflow and dataflow must provide the most adapted to BIM ways to transfer input and output data*. Therefore, the 4D Lean Board prototype development considered already used file exchange formats, and adapted the application to visualization and interactions with these file formats.

Naturally, there are many 3D modeling applications that provide design teams with possibilities to build BIM models (such as Revit⁷⁰ by Autodesk, Archicad⁷¹ by Graphisoft, Vectorworks⁷² by Nemetschek, etc.). But when the users prepare 4D input data for a collaboration session with 4D Lean Board they must export their 3D files into *.IFC format, which corresponds to the Open BIM* exchanges practices and is visualized by Autodesk Forge. Users may upload multiple .IFC files, for example architecture, structure and MEP, into the application. The schedule information comes from *a spreadsheet file (Excel or other) filled according to the requirements of the 4D Lean Board template* (order of columns and fields) in order to provide all the schedule levels views and fill the column with the 3D elements tags corresponding to the schedule tasks. The file is further *saved as a .CSV* file and also uploaded to the application. The 4D link thus is generated automatically by the application.

The output data possibilities e.g., decision-making records were not in the primary scope of the prototyping. However, the application provides the users with the possibility to adjust the schedule, change task statuses and requirements, therefore it records these new versions of the schedule, and the users may access the information as a spreadsheet file. Yet, the collaboration scenario rather suggests that the users will have a way to create a semi-automated meeting report and might *use the application as the project “control board”* thus would not need to access frequently the initial spreadsheet file.

An optimization of the input and output data flow into the project workflow would be a good subject for future work, but now it stands on the above presented limitations.

5.2 Prototype evaluation

5.1



5.2

The current section describes the design of the prototype evaluation by AEC professionals as participants of a 4D-based synchronous collaboration session in a controlled environment. First, it presents the scope and questions (5.2.1). Next, a description of the evaluation variables and data gathering tools (5.2.1.2). Then, it outlines the evaluation sessions iterations, as well as the construction projects and participants. The section main purpose is to describe the design of evaluations structure and context and present the summary of users' feedback.

5.2.1 Evaluation method

5.2.1.1 Evaluation scope

Research topics and hypothesis

Following the research approach to the analysis of collaboration structured with the socio-technical levels, Activity theory and UCD (2.2.2), corresponding to the global "social" context of digital collaboration, and at the activity level, including the interaction of participants (users) and the involvement of mediators - "social and" technical " and the lowest "technical" level focusing on the specification of visualization and interaction for collective use of 4D and Lean.

Thus, the evaluations were investigating the topic of a small socio-technical system for the collaboration sessions: *the collaboration* (co-located synchronous collaboration with digital tools use), *the touch table and screen use for collaboration; and the use of 4D and Lean, as well as prototype design evaluations* (Figure 130).

The macro level of the system is co-located synchronous *collaboration which encompasses the use of the proposed digital tools for project information visualization and decision-making*. The users are provided with the *access and visualization* of the project documentation relevant to the meeting goal. Additionally, the evaluations complete our investigation, and reexamine the emphasized hypothesis:

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team.*

With the evaluations it was important to understand:

- *Digital Collaboration (C1). Do participants accomplish the tasks requested by the evaluation's collaboration scenario?*
- *Digital Collaboration (C2). What do participants require for collaboration flow: project documentation access, protocol, tools?*

The next level of the system is digital collaboration environment: *the touch table and the vertical touch screen*, connected to the project digital data flow and creating the activity environment for the meetings. They first unite the users around the table as the attention and work environment, and second, they provide the visualization and interactions displays. The quality of touch interactions should be as well easy to do and to understand in an intuitive way by the users. Thus, the manipulations and access to the project information would be more equal as well for all the users regardless their domain,

and would also contribute to a stronger collaboration or to a decision-making based on the 4D. This corresponds to the hypothesis:

- *H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration.*

With the evaluations it was important to understand:

- *Digital collaboration environment (DCE1). How do participants perceive the usability and utility of the proposed digital collaboration environment setting more the collaborative decision-making with BIM?*
- *Digital collaboration environment (DCE2). Does the proposed setting allow a more equal access to the project information to all the users during the meeting?*
- *Digital collaboration environment (DCE3). Do users achieve the intended interactions?*

Therefore, following the user-centered iterative design, the evaluations also studied the *user's feedback on the application design and usability*, which also influence the collaboration and users' interactions with the application.

The *core layer is the use of 4D BIM and Lean*, which is studied as the main project information source for the collaboration. In particular, the 3D view, the Schedule view and the 4D link. Regarding the 4D there are two key investigation subjects: visualization and interactions. The quality visualization would provide all the users regardless their domain with a clear and easy to understand visualization of the 3D model and schedule. Thus, it would impact the collaboration and decision-making. With the evaluations it was important to understand:

- *4D BIM (D1). How do users perceive the use and usefulness of 4D Lean Board in their professional practice?*
- *4D BIM (D2). Do users understand the 3D, schedule levels and 4D link visualization of 4D Lean Board?*
- *4D BIM (D3). Do users achieve collaboration tasks proposed by the protocol?*

This corresponds to the hypothesis:

- *H3. A digital tool uniting BIM 4D and Lean scheduling creates a basis for the integration of design and construction dataflows, and is perceived by the users as providing a relevant level of information detail for collective decision-making at every phase.*

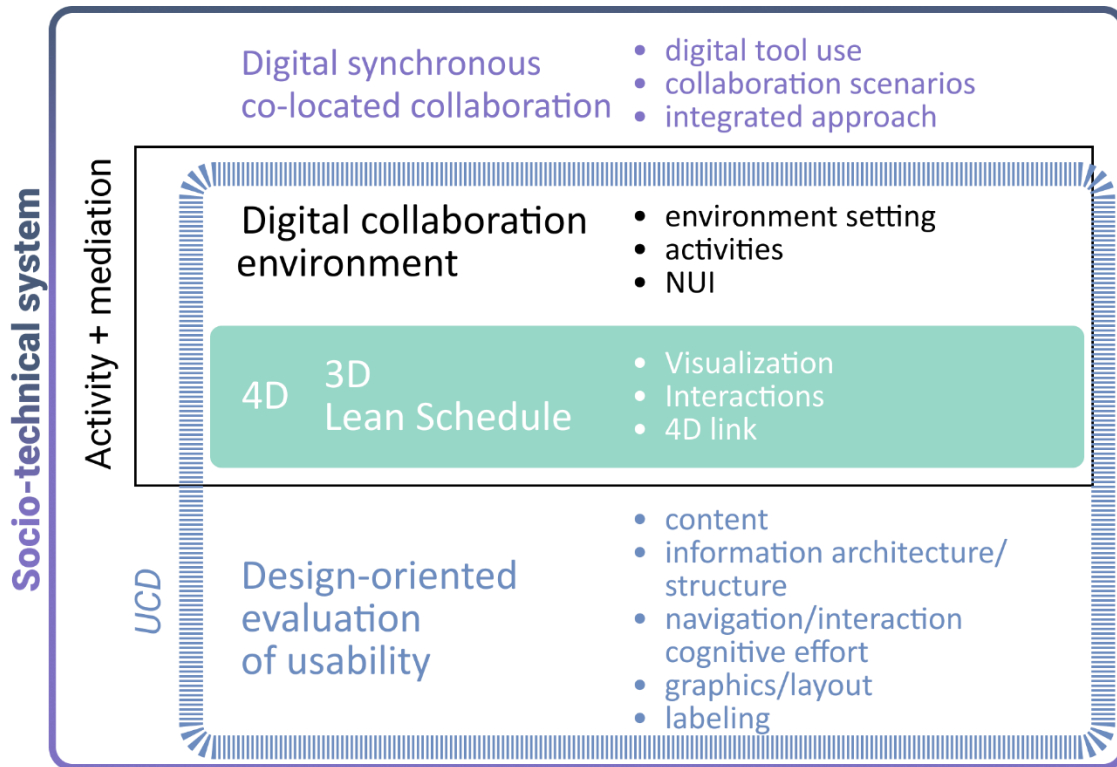


Figure 130 Three levels of a small socio-technical system for the collaboration sessions

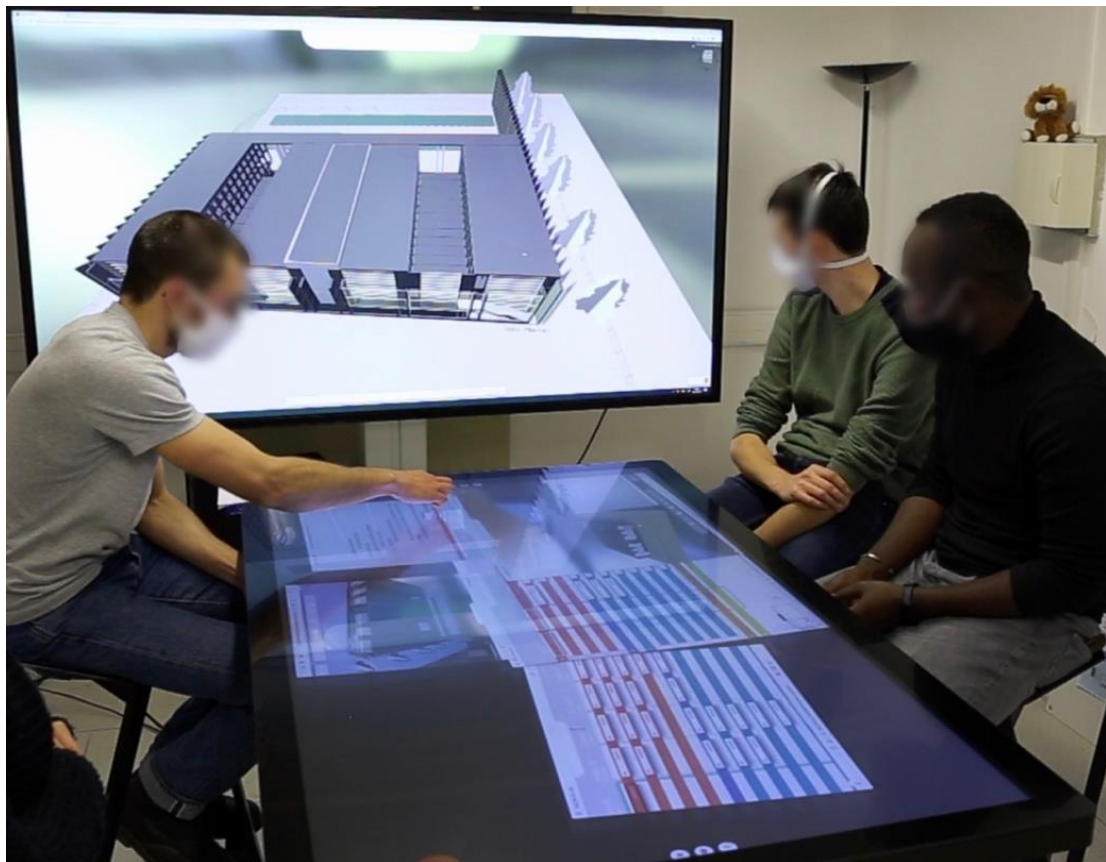


Figure 131 Evaluation session of the 4D Lean Board gathering three participants of different profiles around a touch table with 6 Weeks, Phases and 3D views, and the vertical screen displaying the synchronized 3D view

Evaluation iterations

The *evaluation phase* is a key element for the *iterative design* process (Lallemand and Gronier, 2016b), since it offers to the potential users to test a design solution based on the gathered requirements. Also, the evaluation experiments feedback is further implemented during the design improvement. The *user participation* in the evaluation is very important, since it contributes to a better understanding of goals and activities to the developers, and the tests lead the design and development to a more usable application (Preece et al., 2015). In addition, with usability experiments we have a possibility to run tests within a higher level of control environment than in the field studies (Preece et al., 2015), and thus to focus on aspects more relevant to the research.

Following the *agile development and iterative design*, the 4D Lean Board evaluations by the AEC professionals were held for *every version* of the application prototype. The evaluation's timeline is comprised of 2 major phases, each including three evaluation collaboration sessions, and one additional final evaluation session with Lean experts' (Figure 132).

The first phase corresponds to the evaluations of version 0 (Figure 133) of the prototype after the first three development sprints. It aims *to understand better the needs of the users, to validate elements of the design and to evaluate usability of the proposed 4D*. So, the evaluations were focused on the feedback about the prototype's basic features and concepts of the interface, pertinence of the interactions in a group use context and on the clarity of the 4D link visualization. Since this phase was focused on exploration of ideas, design and technology, it was also important to anticipate the limitations of our prototype development before the second phase started.

The second phase encompasses a series of evaluations of the development progress from version 1 to 2.1 and 2.2 (Figure 133), and to 3 of the prototype. The evaluation focus was on of the *collaboration aspects testing and on design refinement, and on research for more efficient 4D link visualization*.

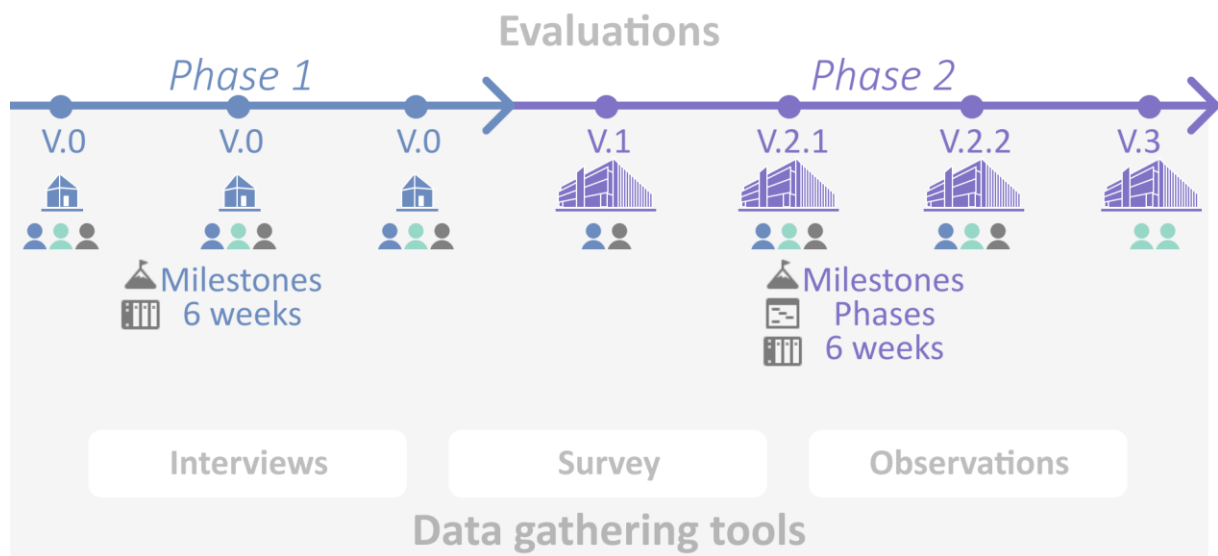


Figure 132 Evaluations timeline schema and data gathering tools

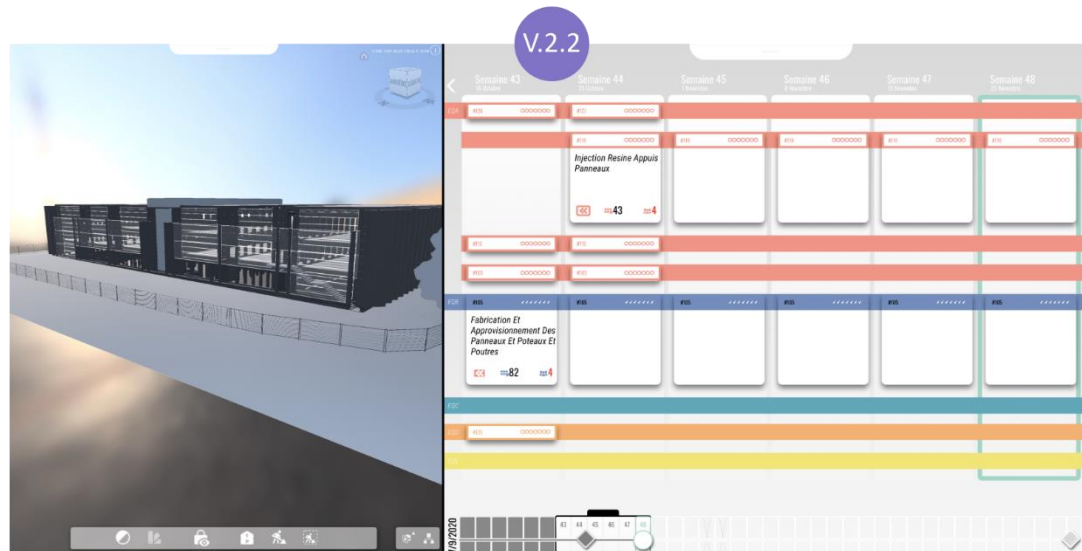
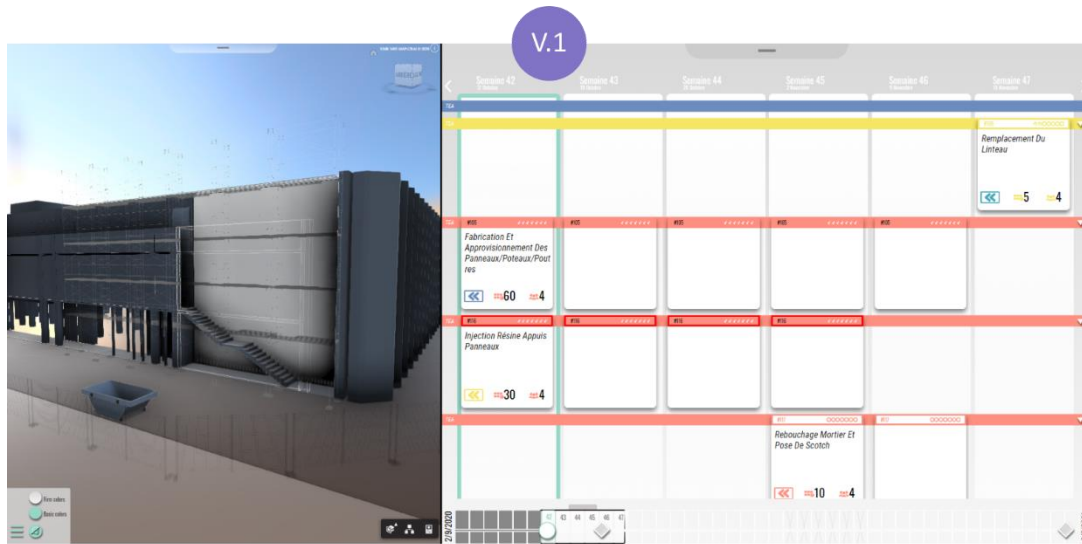
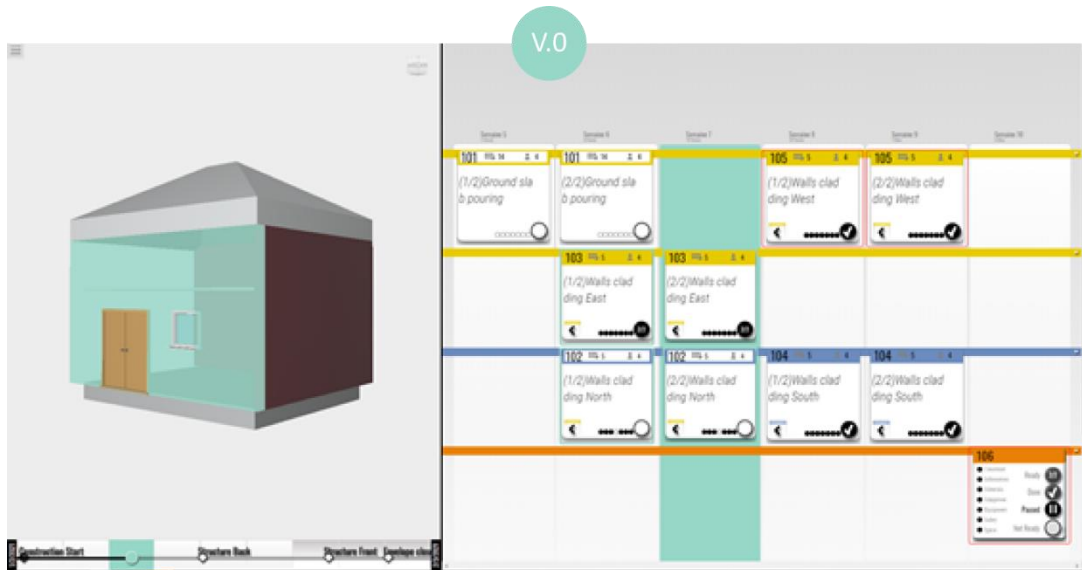


Figure 133 Interface versions summary

5.2.1.2 Evaluation setting and participants

The iterative design process led to the users' needs evaluations, and feedback after achieving certain points of the development. In total we have managed to run seven evaluation sessions. Most of the *sessions had three participants* (except one collaboration session, and another with lean construction experts with each only two participants), gathering different user profiles and collaboration group personas (4.1) around the table. During the first phase the sessions united an *architect, an engineer and a client profile* around the table so they would provide a generic feedback on 4D Lean Board concepts. Phase 1 evaluations were exploring a variety of aspects, but due to the early stages of the development they mainly fostered the interface evaluations. Since at the second phase the scope of the evaluations shifted from the exploration mainly to the targeted development of schedule levels and collaboration improvements, the participants selection was also different to correspond to the evaluation scenarios.

Moreover, we gathered the information about users' background, years of experience, as well as the experience with planning and scheduling activities, 3D, 4D and Lean construction (Table 33).

Table 33 Summaru of the evaluation phases and participants

| Phase | Session | Version | Group | Participant ID | Role | Background | Years of experience | Years of 3D use | Scheduling experience | 4D use experience | Lean construction |
|------------------------------------|---------|----------|-------|----------------|--------------|-----------------------------------|---------------------|-----------------|-----------------------|-------------------|-------------------|
| Phase 1. Interface evaluation | 1 | V0 | GR1 | U1 | Design | Architecture | 4 | 8 | Familiar | Familiar | |
| | | | | U2 | Construction | Civil engineer | 4 | 1 | Yes | - | Familiar |
| | | | | U3 | Client | Architecture | 1 | 6 | - | - | |
| | 2 | V0 | GR2 | U4 | Design | Architecture | 5 | 10 | Familiar | - | |
| | | | | U5 | Construction | Civil engineer | 2 | 7 | Yes | Yes | Familiar |
| | | | | U6 | Client | Advanced modeling | 1 | 1 | - | - | |
| | 3 | V0 | GR3 | U7 | Design | Structure engineer | 25 | 15 | Familiar | - | |
| | | | | U8 | Construction | Architecture | 1 | 3 | Familiar | - | Familiar |
| | | | | U9 | Client | Advanced modeling | 1 | 5 | - | - | |
| Phase 2. Collaboration Scenario | 4 | V1 | GR4 | U10 | Design | Architecture | 25 | 15 | Yes | Familiar | Familiar |
| | | | | U11 | Client | | 2 | 6 | - | - | - |
| | 5 | V2. 1 | GR5 | U12 | Design | Architecture | 5 | 14 | - | - | - |
| | | | | U13 | Construction | Architecture | 5 | 8 | Yes | - | - |
| | | | | U14 | Client | | 4 | 10 | - | - | - |
| | 6 | V2. 2 | GR6 | U15 | Design | Architecture | 4 | 10 | - | - | - |
| | | | | U16 | Construction | Civil engineer | 2 | - | Yes | - | - |
| | | | | U17 | Client | Architecture, Facility management | 1 | 12 | - | - | - |
| | 7 | V3 | GR7 | U18 | Construction | Civil engineer | 15 | 2 | - | - | - |
| U19 | | | | manager | | 6 | 3 | Yes | Yes | Practitioner | |

We chose to *invite different groups* of people for every evaluation session, since the variety of users points of view, background and feedback were in the priority scope. Even though it is also typical for a user-centered approach to work on a product evaluated by the same group of users. In addition, the sessions duration and frequency would have been time consuming for the AEC professionals, thus it was difficult to arrange the same testing group for every evaluation.

Construction projects choice for evaluations

We used two construction projects for the evaluation sessions. At the first phase, a simple cabin of four walls and a roof (Figure 134), as the project of ten construction elements was the subject at the collaboration sessions. The *extreme simplicity of the geometry* and of the schedule fostered the understanding of the construction project by the evaluation participants. Thus, the focus of the users

was not distracted by the project complexity, and they could discover all the features of the 4D Lean Board interface, and evaluate the 4D link visualization and interactions.

During Phase 2 of development and evaluation, *the project of reconstruction after an accident of façade collapse* of Nancy School of Architecture (Figure 135, Figure 136, Figure 137) was the subject of collaboration sessions. The reconstruction project is a real project with real scheduling and challenges. It consists mainly of the works on façades reconstruction and structural reinforcement of the prefabricated concrete blocks. The project requires interventions in four different zones and on every level.

Also, since the Architecture school had to be ready before the beginning of the new school year, construction contractors and subcontractor interventions must be managed efficiently and on time. In addition, this project provides us with multiple types of project elements and tasks (new, demolition, temporary) and it includes the existing elements of the building as well. Such a context is adapted for 4D link visualization studies, quick understanding of the construction aims and tasks by the evaluation participants, and the possibility to present the prototype with the real construction team of the project.



Figure 134 Simple construction project photo used as a subject during Phase 1

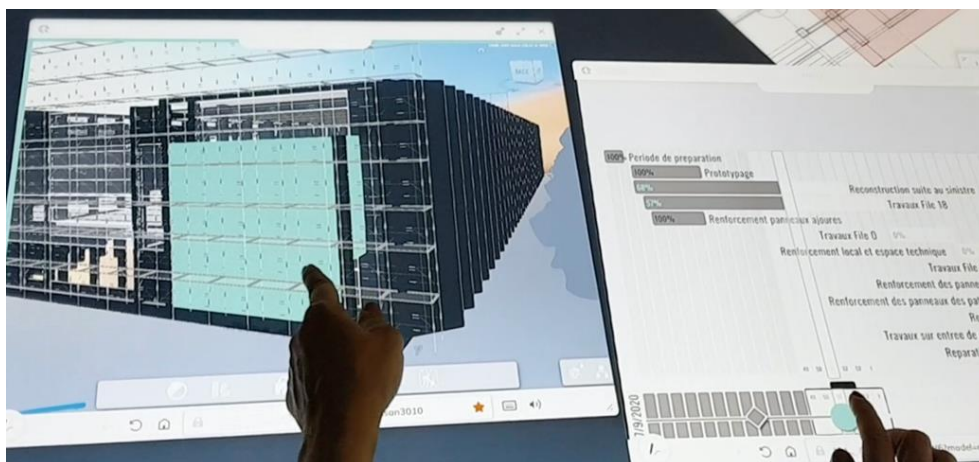


Figure 135 Example of the prototype interface during the Phase 2



Figure 136 Photos of Nancy School of Architecture: a - view of the façade after the accident, b - view of the façade during the reconstruction, c - view of the façade after the reconstruction



Figure 137 3D model view of the reconstruction project of Nancy School of Architecture

Evaluation session steps

All the sessions were following a scenario of 6 steps (Figure 138), which included specific tasks and actions adapted to the goals of the evaluation phase. For example, following the briefing and main 4D Lean Board features general outline, the “*five seconds test*” (Lallemand and Gronier, 2016b) was the first part of the evaluation protocol very. Such a quick test allowed to gather *the first impression* and the users subjective vision of the application. Thus, it indicated the general quality and speed of understanding of 4D Lean Board interface and its features.

Next, the evaluation protocol offered users the possibility *to explore all the features of the 4D Lean Board interface and to interact with them*. The users were asked to “think aloud” during their explorations to give an understanding of the perceived and real application functionalities. Following the exploration stage, the users had specific questions to answer about the construction project pushing them *to seek the relevant information* in the 3D view, in different schedule level views or in the 4D link. To conclude the users were tasked to first *study the proposed construction method, sequence, schedule and team assignment*; second *propose a schedule optimization*. Such tasks included interactions with the project information, discussion and collective decision-making.

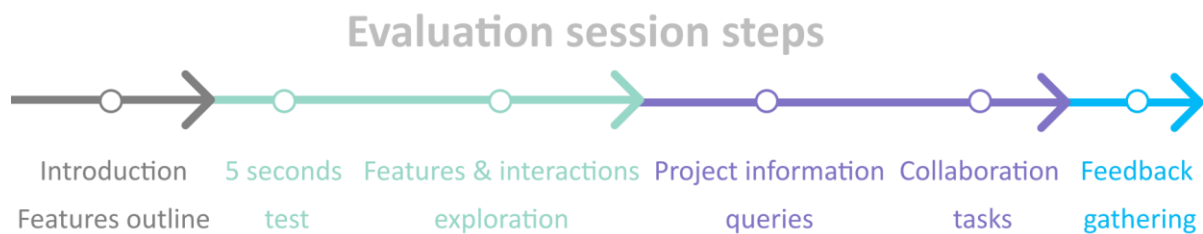


Figure 138 Evaluation session steps

Data gathering tools

For the evaluations data gathering and users feedback we chose to rely on a customized combination of tools. One of the reasons to use a *combination of different tools* for evaluation data gathering (Figure 132), is that such an approach provides different perspectives within the same research (Preece et al., 2015). Thus, after the sessions, the feedback was gathered with the use of *questionnaires and semi structured interviews*, which were aiming to evaluate specific design features and usability, since the techniques are best suited to the aim’s specific goals. The data from questionnaires and interviews was also completed by the *observations* from the collaboration sessions. Therefore, it provides us with a possibility to better understand the users and their feedback, as well as interpret the experiment results. In addition, the observation is particularly useful on the early prototype development stages since it broadens the understanding of the users’ needs.

The semi-structured interviews with the group of users after their evaluation session were the main feedback source. The structure of the interview covered the themes used further for the analysis yet gave enough flexibility to the users’ expression. The interview themes were gathering the *users’ opinions on the sociotechnical levels, application usability and their opinion on the use of the 4D Lean Board in their practice*.

Interaction evaluations often rely on usability scale measurements providing the user feedback on the perceived system usability. The scales also assist with the comparison of different version of the application, and provide the perspective from the different users on usability.

Computer System Usability Questionnaire (CSUQ) (Appendix A) was developed to evaluate user satisfaction and usability of the systems by Lewis in the 90s can be used for evaluation of any kind of a system (Lewis, 1995). It is comprised of 19 items and to summarize evaluation on the categories: *utility, information quality, interface quality, general satisfaction*. However, with the technology progress the evaluation tools have also progressed. The evaluation of website is often done with the *Design-oriented Evaluation of Perceived Usability (DEEP)* (Appendix A) (Yang et al., 2012). This questionnaire is a combination of items from the previously mentioned Computer System Usability Questionnaire (CSUQ) and with Practical Heuristics for Usability Evaluation (PHUE), Questionnaire for User Interaction Satisfaction (QUIS), System Usability Scale (SUS), Purdue Usability Testing Questionnaire (PUTQ), USE and Website Analysis Measurement Inventory (WAMMI) surveys. Users evaluate items value on a 7-points Likert scale. It is comprised of *content, information architecture/structure, navigation/interaction, cognitive effort, graphics/layout, labeling*.

These questionnaires are relatively short and may be filled by the users in relatively brief time. This was particularly useful for our evaluations since the professionals had only limited free time for the evaluation participation. The Design-oriented Evaluation of Perceived (DEEP) questionnaire covers more categories, but it is rather used for website evaluation. In our case we develop a single page web application. In addition, the prototype comprises meaning features specific to AEC and multiuser collaboration. However, the average scores on the items did indicate the perceived weaknesses of design. These evaluation tools were *particularly useful for our iterative design since* they gave precise feedback on the prototype usefulness and on the categories related to the design. We chose not to gather information on user experience through the surveys for the iterative design. The quantitative data only completed the user feedback from the interviews qualitative data. We did not run any statistical analysis with the gathered quantitative data due to the insufficient number of participants for valid statistics results and focus on the exploration objectives through UCD.

Though today there is an argument that the Human-computer Interaction evaluation should focus on user experience and not on the usability. In our data gathering, the user experience evaluation elements were noted through the observations of the collaboration sessions.

The observations of the evaluation sessions helped to track the recurrent users *slips and mistakes*. The slips tracking is important because it illustrates the intention for one action, but which results in another and therefore illustrates the weaknesses of the design. And they are either action-based or memory-based slips. Also, as Norman suggests they may be sorted in three major classes: rule-based, knowledge-based, and memory-lapse (Norman, 2013). In our case *the knowledge-based mistakes are particularly important* to track since the users are facing a complex solution or probably have no previous skills or experience with 4D nor Lean. Thus, such mistakes would indicate the weak points of the application structure and design and how to constrain and guard users better.

Due to the nature of the research context of AEC, amongst the independent variables we would consider all the digital documents of the construction project, and mainly all the aspects related to the nature of the construction project used as an example for evaluation sessions. Such variables as: *the usability scores and interviews feedback and user's profiles influence on a use of the application*; are important for the usability evaluation. Also, an observation *of the interactions with the different application elements and displays* would provide a better understanding of the interaction dynamics. The user's *errors and questions* complete this information. In addition, the observations of the *conversation intensity and the required time to achieve the scenario task* would also indicate the decision-making flow.

5.2.2 Evaluations summary

This section summarizes the feedback gathered through the interviews, observations and survey from the evaluation sessions of the BIM-based synchronous collaboration, on the use of the digital collaboration environment comprised of a touch table and a vertical screen, and on 4D Lean Board use.

5.2.2.1 Collaboration and digital environment

Digital collaboration scenario

Several evaluation participants described the 4D Lean Board as *a perfect tool to explain the project at the first construction meeting*. According to U15 such digital tool would be extremely *helpful for the construction preparations*, to foster quick understanding and bring everybody ‘up to date’, arguing “... when we start the construction, it is difficult to rapidly understand the project and comprehend all of its’ complexity”. Moreover, the participants commented on useful possibility to adapt the setting and the prototype’s interface to the meeting goals and participants, for example U16 perceived the proposed prototype as “... truly useful for conversations with the client”. However, Groups 5 and 6 have expressed their concern that “*today not everyone is ready to participate at such [collaboration with BIM and Lean] approach*”, thus it would require some shift of practices not only towards BIM but also to the more lean and integrated management methods.

The participants also perceive 4D Lean Board as a relevant *collaborative tool for construction planning* meeting. They find it useful for the meetings to evaluate the project progress, U10 comments on look ahead schedule view “... certainly interesting for the foreseeable future construction planning.” The participants also highlight that all the necessary information *elements are present for an efficient decision-making and planning*, however, for construction activities coordination there is still another, more detail level of schedule to be developed.

Most of the participants outlined that in a given short time of the evaluation collaboration session they quickly got *the understanding* of interactions which appeared intuitive, and highlighted the ease of use of the touch table and prototype’s interface, and even highlighted that only a *few additional sessions* would make them completely confident in their skills. However, U14 outlined that “... even without knowing the tool. We still succeeded and worked well. The use of the tool is consistent and interactive.” Therefore, the rapid new skills development should be expected.

The participants also emphasized concerns about *legal aspects* of collaborative planning, since the tool offers not only schedule visualization, but also the adjustments it may become *essential to limit the schedule modification rights* to avoid conflicts from the legal point of view, as outlines U17 upon the need for access limitations: “... if everybody is allowed to make adjustments it could rapidly become chaotic”. For example, Group 5 suggested that during the meeting only one 4D Lean board user, for example such as construction manager, would have the permissions to do the planning adjustments, and they *appreciated the idea of the password protected access* to the construction team and crews task assignments by the leader. All the participants of Groupe 5 highlighted the need to be able to adjust the schedule, but they expressed a remarkably high concern about the *value of the schedule as a legal document with the obligations*, therefore, any adjustment or modification of it may provoke penalties for some parties. Hence, the participants think that to be able to integrate such tool into their decision-making not only for visualization, but as a main progress management support, there is a need to *adjust their business process to a more trusting collaboration and to lean management*. The current version

of the application did not cover the *conflicts management*, but the participants have highlighted that it could complete the application functions in the future.

Within the same ideas to broaden the use of the tool, and to avoid the accidental schedule modifications or surplus of unused interface elements, Group 5 also suggested to clearly distinguish three modes of the prototype, such as a *'visualization mode'* for discussions, presentations and communication in general, then an *'annotations mode'* to record suggestions and decisions, and finally the *'schedule adjustment and progress management'* mode allowing any modifications. This last mode would naturally be accessible to the dedicated users. Such an approach by mode would already be more reassuring for the users regarding their legal responsibilities on the project.

In addition, U16 outlined the need for *meeting reports production* in a more automated and digitally integrated way: *"... it would be helpful to take notes and annotate the documents. For example, I could take a pen and write directly on a document and share it immediately."* U12 also highlighted that every meeting is completed with a report, and described the *need for interactive annotations* to such reports, giving an example of interactive stickers application to the project plan allowing such annotations.

U13 highlighted that *"... it takes a lot of time to edit the meeting report, sometimes a few hours, and then takes time to get every subcontractors validation of the report, which may arrive right before the next weekly meeting"*. Thus, the participants request in the future after a weekly construction follow up meeting with the 4D Lean Board to be able to export an *automated and official meeting report, ready to be signed*. Thus, they imagine that the prototype has a great potential to be the one and uniting tool to manage all the construction meetings documentation, feedback and orders. Some participants even *imagined a possibility to record the interactions and annotations through the personalized pens* or voice recognition system for every user, to make the meeting reports in a more automated way as well.

Digital collaboration environment: multitouch table and vertical screen

The same multitouch table was the constant element for all evaluation sessions, except the session with Lean construction experts using a small touch table. Thus, we were able to gather comprehensive feedback on a use of such a tool at the meetings. Moreover, the prototype evaluation feedback extends the feedback from the use of such a tool from the pedagogical experiment.

Most of the participants expressed that it was very *pleasant to use the multitouch table*. They also expressed the appreciation of the table being a uniting element for all meeting participants who had to be using the same tool and gather their attention around it, U17: *"it is nice to be gathered around the same tool. Even we are working with separate windows, the fact of sharing and interacting with the same thing is useful."* The resemblance of the touch table to a common table was appreciated as well. Furthermore, some think that the touch table use even *brings a playful aspect to a meeting*, and it also fosters *more 'democratic' and collaboration* since most of the evaluation participants perceive it as an easy tool to interact with.

Group 6 comments that the table's size seems to be right for a small meeting of a group of 3 to 7 people, and that the large size of the digital project documents and the possibility of "zoom in" or "scale" guarantees a high visualization quality. In addition, they *appreciated the ability to visualize multiple project documents at the same time*, since an easy access to the project information was useful for their discussion and decision-making. However, some participants never looked for any additional information nor tried to remove the surplus documents from the table's display, despite the easy access and dynamic discussion.

The vertical touchscreen was also a part of the evaluation sessions setting. The vertical screen's purpose was to *augment the surface for display*, and to provide the 4D Lean Board users not only with the collaboration interactions tool, such as the table, but also with a more suitable tool for presentations and complex information display. Thus, the vertical screen provided visualization of the 3D view which was synchronized with the table's 3D view during the evaluations.

The feedback on the utility of the table is positive and almost unanimous, however the setup including the vertical screen was not perceived as necessary or helpful by half of the participants, regardless the evaluations phase. Groups 4 and 6 did find the screen extremely helpful for more detailed visualization. They were even using the *3D model view on the table as the interaction "interface" synchronized with the 3D model view* on the vertical screen as shared large view of the project. On the other side Group 5 almost *did not pay attention to the vertical screen* and the displayed 3D view, thus did not feel the need for it during their session nor after while providing their feedback on the equipment. Thus, two groups from the three approved the synchronization of all the 3D and scheduling views on the table and the screen, and found it extremely useful, and *welcomed the presence of the vertical screen* for a better display of the 3D and gain of space for the schedule views on the table.

In addition to the digital collaboration space of the touch table and the vertical screen with the collaborative software, the evaluation participants highlighted that it is particularly important *for them to have a private tablet or a notepad* at any meeting to take notes. For example, U15 point out that *"at the construction site we are used to the tablets, and it would be nice to have the same view on a portable tablet"*. Thus, the digital collaboration space should be adapted to this user's need as well.

After the collaboration session Group 5, even though they enjoyed the use of the table, suggested to replace the table with the individual small tablets as a test. The participants are used to the individual tablets use for the construction site visits and follow ups. They also already have *a habit of bringing a video projector* to the construction site and the meetings. Thus, as an *alternative to the low mobility of the system of large touch table*, vertical touch screen and a computer, and other factors such as the need for security, comfort or technical services, the participants imagined a solution with a projection of the meeting documents on an ordinary table even without the gestures recognition system, but connected to the individual tablets. This is a possible adaptation of the already existing in the practice technologies and procedures.

Despite the expressed concerns about the table utility, the participants appreciated that 4D Lean Board is web-based, and thus accessible from any tablet during construction management. The individual tablet may *thus be complementary to the table*.

Concerns and reservations about the proposed system use

Since most of the participants were from a French AEC context, they had as their specific to the context practices and ways of proceeding in mind, naturally they often had various reservations regarding BIM use, collaboration protocols and legal aspects. They also inquired about the touch table system cost, mobility and had *concerns about its' usefulness for small projects*. For example, when Group 5 was discussing the potential integration of a large touch-table system into a real project, they would see the system installed in a construction site office, thus needing to secure it. Also, according to U12 an U13 perception the usefulness of such tool must be only for a project with a cost from 20 million euros, and that the easiest integration and benefit would be for communication, for discussions and project visualization by the real estate developers or architecture firms when they meet the clients.

The evaluation participants also suggested that *the benefit of such system integration into the project workflow would be gained only by the professionals who have already adopted BIM* or for a large construction firm. They were also expressing opinion that an integration of such system might *require some effort from their conservative colleagues*, especially during the construction phase of the project, as outlines U15: “... not everyone today will be willing to participate in meetings like this”.

Group 5 participants were concerned about AEC professionals who do not work on design, 3D or project management, and who are usually focused on 2D documents and construction tasks, thus not willing to learn how to collaborate with the new tools, or not even see them as serious work tools.

Only a few evaluation participants have seen the 4D during their studies or professional career, thus most of the 4D Lean board feedback is gathered from the users who are relatively new to the 4D or nD BIM simulations. Therefore, they were *expressing interest in the costs, time and skills required to create a 4D simulation*. In our case the input data for the 4D Lean board are the IFC files and a schedule spreadsheet table (an Excel file saved as CSV). Thus, in order to prepare the project information for the collaboration session with 4D Lean Board, the 3D models must be exported as IFC files, and the construction schedule must follow the prepared template with the columns and rows adapted to the Lean levels of the schedule, contain all the usual information from the Gantt charts about tasks names, duration, types, etc., but also the 3D elements IFC IDs to create an automated 4D link between the task and the elements of the model. So, in a way, the additional step in comparison to the preparation of the data for a not 4D based meeting is the input of the 3D elements IDs.

Certainly, these reservations indicate the perceived limitations for a direct adoption of such innovations into the common practices. They indicate the important aspects of the current context, and the requirements to consider. Yet, the facilitation of potential integration of prototype proposal into already existing common project development practices in France was not the main aim of our research.

5.2.2.2 4D BIM and Lean schedule use

The 4D visualization, interactions and adjustments are the core purposes and functions of the prototype, thus the feedback on 4D simulations quality, as well as the 3D view and schedule views are central to our evaluations.

4D BIM

During Phase 1, the evaluation participants were referring to the *4D simulation as rather interesting and useful*. According to the participants feedback it was a useful visual assistance to see the 3D model and the schedule connected to rapidly understand the project. This possibility to rapidly understand the schedule sequence was *especially appreciated by the participants less experienced in 3D* modelling and construction.

To have more clear understanding and display of the necessary elements to decision-making, the participants highlighted the need to have 3D and 4D filters by the *3D file origins* (architecture, structure, MEP, etc.), by the type of construction tasks and responsible teams, construction zones. Such filters may be already used in 3D visualization software, and in our case, it was important to apply them not only to the 3D but also to the schedule view, thus the 4D. In addition, such filters would be useful not only for decision-making but for the construction progress management. For example, they have an idea about *'filtering' the construction crews* and their responsibilities at the schedule, and choose a color code for every crew.

The users also highlighted their appreciation of the *perceived to be very intuitive* and responsive touch gestures to interact with the 3D model. However, they expressed the need for a quick navigation tool, like the *3D navigation cube*, with the preset views, such as “front”, “back”, “top”. Also, even though the interactions seemed very natural, they needed some time to understand the touch interaction details such as the functions of “tap,” “press,” “2 tap”. Also, to serve the clear visualization and 4D highlights purposes they offered to *automatically change the 3D camera’s position* when the 4D simulation ‘play’ is in progress to point to the 3D elements connected to the schedule.

The participants interactions with the 4D simulation highlighted the need to *improve and investigate further the 4D visualization*, since they were missing some elements of the model and needed a clear *distinction of the tasks to come, tasks ongoing and tasks done*.

Further, Phase 2 included the evaluation of the 4D filters and schedule levels, as well the visualization of the test project based on the real construction project. Thus, the feedback is more focused on confirmation of the previous suggestions, and on the evaluation of visualization effectiveness and usability for decision-making.

The feedback on *the suggested filters, camera movements and 4D link feature* highlights were positive. The usefulness *of the 4D filter by teams was highlighted* by the participants most accustomed with construction management. However, they have pointed out to a *limitation that more than one team may be working on the same 3D element attached to different tasks*, therefore indicated the potential flaw of the visualization. This comment should be taken into future development consideration.

The participants appreciated that the *4D unites two complex information types* in the same system. Some participants said that for them 4D was a very convincing tool to emphasize the project. According to their feedback, the 4D link is well highlighted and easy to comprehend, as well as the navigation from a schedule task to the related 3D element, as emphasizes U17: *“It is nice to visualize various project documents of various nature, and it is also dynamic. The 4D offered the highlight, automatic change of view in association with the selected items, it is allowing us to see the link between different information aspects”*.

An easy gesture of the cursor movement on the project timeline or task weeks was perceived by the participants as the more *efficient way to navigate the 4D simulation*, and as the demanding less effort than an alternative unconnected 3D model and Gantt schedule visualization. Also, it was *easy to choose any specific point* on the project timeline. This was confirmed, not only by through the interviews feedback, but also from the collaboration scenario and interactions observations.

However, the users insisted on the need to be able to outline and ‘isolate’ the view on only the 3D elements coming in the chosen frame of the 6 weeks, and not necessary all the project, naturally when the 6 weeks level of schedule is activated. This mode was requested for easier understanding of the construction progress and the follow-ups. In addition, the easy access to all project documents must be provided to the collaboration session participants as well.

An observation made by the participants of Group 6 is that a *4D simulation illustrates well and clearly the important need of collaboration*, and that none can work on a construction project alone. The different roles, such as architect, client, engineer or construction specialist were more explicit for the feedback at the second phase.

For example, the client was pleased to be presented with an interactive project representation rather than with technical documents, such as plans or details, U16 *“for me as the client, the 4D was*

extremely helpful, since the plans and technical documents are not always easy to understand, but here we can turn the model. Even for someone who has never been to a construction site, understands the project, the scale, the link between the objects.”

The architects were the most active users of the filters and 3D navigation, as well as of the phases schedule level, 4D simulation play, U15 outlines that: *“the phases view is similar to Gantt and allows the necessary schedule visualization before the construction”*.

They were also commenting on the potential usefulness of the vertical screen for the presentation in front of the team. The construction and scheduling specialists were more *pleased to discover all the functions of the tasks level of schedule* and commenting about the use of it for follow-ups and construction management.

The participants also outlined other ideas for further development, such as U15 suggesting not only the 3D visualization, but also the need to display the plan view *“... could be interesting to also have a connection not only with the 3D but also the plan view”*, which is for now possible through the 3D section of the model.

4D and Lean schedule levels

Most of the participants never had any experience with lean construction management, only some have been familiar with its principles. Thus, their feedback on the use and usefulness of lean levels of schedule visualization for 4D simulations is from the point of view of someone who discovers the concepts and explores possibilities. Naturally, the most complete feedback was from Phase 2, since it offered milestones, phases and look ahead six weeks levels of the schedule.

At the first phase the evaluation was aiming interface features evaluation, the participants have managed to *quickly understand* the small test project and the number of tasks on the schedule, they also quickly understood *the idea of the ‘sticky notes’* representing tasks. Since the participants appreciated the 6 weeks look ahead schedule as a time frame, they felt confident that they would have understood even a more complex, realistic kind of schedule as well.

Since the schedule representation by levels and the task representation with the sticky notes were new to the participants, they had many questions and suggestions on the subject, specifically about the displayed information. For example, they have highlighted many *ways to improve the design and labeling*, as well as the need to have an efficient indication of the task readiness and progress status.

During the second phase the participants were not only asked to evaluate the usability, but also to resolve specific problems referred to as evaluation collaboration tasks. For the session of Group 4 the Version 1 prototype of 4D Lean Board did not yet have the schedule adjustment option, however, the session participants managed to achieve the proposed collaboration tasks and the decision-making on the project, they also suggested some schedule adjustments and requested the schedule modifications option development.

Group 4 participants also highlighted that such digital and interactive project schedule was *easier to understand* than the classic one, even they are rather used to the table sheets and .pdf summaries. They found it particularly useful *to be able to choose the schedule level of detail*, which are easy to understand and to read. Since the 3D and schedule are connected, U10 and U11 thought of a possibility of the *separation of the schedule visualization in separate windows to have more immediate access* to those and just minimize the window size if not used for collaboration. In this way they benefit from the touch

table display size and the interactions with the digital documents have a close resemblance to the paper documents use.

The participants have highlighted that the prototype could help them *not only with visualization of a schedule, but also with a comparison of two different schedule offers*. Such a comparison would be enhanced by the 4D link and would be useful at the pre-construction phase.

Like at Phase 1, the users of the prototype at Phase 2 *appreciated the 6 weeks look ahead* schedule as a time frame. They described it as useful and interesting, as not only the schedule visualization but especially handy in link with 4D.

During the evaluation session of Group 5, U13 rapidly explored the project and the tool and further led the discussion, which resulted in a naturally defined leading role and behavior. The participants achieved the required collaboration tasks, without precipitation but through the *detailed project and tool exploration and discussion*. Further, U13 evaluates 4D Lean Board emphasizing, that for the proposed tasks “...even if we had only the phases schedule level or the Gantt, we would already be able to collaborate, and be able to resolve all the planning problems quickly”.

The 3D styles and 4D link visualization was one of the core subjects for the research, and the vivid subject of users’ discussion. Group 5 took time to understand each 3D visualization style meaning, and emphasized that the proposed styles are useful, but detailed explanations are required to understand their significance. The participants hypothesized that the use of vivid and *explicit colors would be easier to understand for the construction crews*. They also comment on 4D mode by team with 3D style applying the team color filters to the elements, U13: “It is great to have team colors on the model and on the schedule, we can clearly tell here that Team A is in charge of scaffolding, for example”, the other two users strongly agreed.

The participants *interacted enthusiastically* with the schedule and the 3D in efforts to understand the project as well as possible. During their explorations, they emphasized the need for a zoom on a 3D element when selecting the related task. The camera adjustments like zoom in or pivot, when the construction sequence is ‘played’ to provide the better emphasis of the link between 3D elements and the corresponding tasks, U14 emphasized the possible solution with a scenario where: “I go the look ahead schedule, click on it and the connected model element is emphasized, highlighted, and centered in the view”. The proposed feature was implemented. In addition, U13 completed the comment with the request for the link not only with 3D perspective or axonometry view, but also with the 2D view.

Most of the participants, not familiar with Lean needed to consult the Gantt chart of the project. A non-interactive image of the project Gantt chart was available to the participants during the Phase 2, once Groupe 5 have discovered the Gantt view, they felt reassured, U12 commented “this I understand”, even if they did not use it for collaboration. Yet, the participants of Group 5 were curious about the new for them representation of construction schedule with Last Planner levels of detail. But they confirmed, that even though they are *used to the Gantt* charts and would typically want to see the *critical path, the phases level of detail of the schedule should be enough for discussion on pre-construction*, and the tasks level of detail should already help with the more focused on details preparations and construction works.

The participants from Group 5 gave a lot of thoughts to the implementation of 4D Lean Board to construction management and progress survey, and had many suggestions. The participants expressed an interest in having an *integrated management of the modifications and updates* of the project. For example, if there is a design update the task would have note only connection to the 3D element on the model but also a recording and access of the previous design.

As another example they expressed the possibility to use the tool not only to visualize the 4D simulation and other project information, but to *use as the main tool for a comprehensive progress management*, but to do so they would also like a possibility to *add survey reports, to track and claim the errors and responsibilities*. For example, they need to easily access the previous week's meeting report on the decisions and actions as the first thing on the meeting agenda, thus the tool and the use scenario should help with that. According to U13: *"This could be a rely great tool to track the conflicts with clients or contractors."* In this scope they have also highlighted the *importance of an easy access and of a clear visualization* of what has been already done and what is to be done next during the construction follow up meetings, which is achieved through the 4D visualization styles and task statuses.

In addition to the proposed quality project visualization, the participants think that an *efficient way to annotate the tasks and 3D model elements is also particularly important for the progress survey*, thus they would like to be able to add such annotations or even to add progress photos from the site to the tasks. They see it *as a control board and a communication support*. The participants appreciated that in the task requirements they may have the *information about the materials orders, security protocols and construction procedures*. They also appreciated the possibility to indicate vacation days on the calendar.

The Group 5 participants also expressed some concerns about the *need to remember the order of the task requirements to understand the summarized view* of the checked and unchecked requirements on the sticky note. However, they had no problem with accessing this information with the task requirements detailed mode. Also, they said that once they start using the requirements as a part of their project management as the habit it should not be a problem.

Group 5 participants were also looking for a way to survey the tasks progress and to label it clearly. For example, they described a possibility to add a special color code for the task requirements status. But since the color is already used for the construction teams 4D filter, they *suggested further the modifications of the head of task the design* of and of the task ID labeling.

During the last evaluation of the prototype by the users as a group with different roles, the participants of Group 6 evaluated the most advanced version of the prototype (except the modifications of the planning option in Version 3). They had some time before the session to get acquainted, which fostered more natural discussion. The architect and construction manager invited to the test provided their expertise, also the group had the input from U17 bringing the perspective of the *real client of proposed reconstruction project* to the collaboration session.

Thus, the participants did not hesitate to explore 4D Lean Board features, rapidly resolved the proposed collaboration tasks of identification of the planning issues proposed by the experiment's scenario, and they have found the planning issue in a task duration almost immediately and observed as well the "construction elements order error" with the help of 4D simulation.

In addition, U15 and U16 explored the intervention of each construction team in details. *All the users interacted with the 3D view and the planning view* during their discussion, and they even tried to create a report of the meeting with annotations and the screenshot of the errors highlights.

This group also *used both the table and the screen*, and repeated the same behavior as Group 4, where the 3D model view on the table was used as 'a navigation view' for the touch gestures, but all the users looked at the model on the large screen. Group 6 perceived as useful the proposed 4D visualization of the project model and planning, and enjoyed the exploration of the proposed 3D/4D filters.

From the production overview perspective, the construction manager U16 comments on the prototype features “... *all the elements are already present in general for production weekly review, but the CPM visualization would be always useful as well*”, he emphasized the value of the tool as a control board providing the general preview of the progress. Also, U16 highlighted that “*to manage the teams it is useful to have all the information about the team in the same place*”. U17 completed the comments with the request for “a less ‘fixed’ post-it” emphasizing the intuitive wish for interactive and very dynamic use of the look ahead schedule.

Evaluation session with Lean construction experts

Version 3 of the prototype, enabling schedule modifications of the levels of phases and tasks was evaluated by U18 and U19, Lean construction managers with some experience of 4D use. The evaluation was not held in the same environment as the previous sessions, but still enabled by the small touch table and the vertical screen.

The participants did not hesitate to explore the proposed project model and schedule, thus they did ***not hesitate to try various interactions*** supporting the discussion, such as 3D navigation, planning replay, tasks details overview. Every discussion step was combined with interactions with 4D Lean Board. Moreover, the participants did not verbally express confusion during the interactions. Thus, the users examined the project planning proposed by the experiment scenario, and they found the schedule issue of the certain task duration almost immediately. By doing so they achieved the first evaluation task. Yet, they did not need to rely on 4D simulation use as a medium, the examination of the planning was sufficient. Further, they examined the 4D simulation to verify the consistency of the construction order, and identified the ‘error’ in the order of the construction elements.

Since version 3 of the prototype allowed not only the visualization but also some modification of the proposed planning with the adjustments of the phase and task order or duration, they provided feedback on modifications as well. They highlighted the need for more interactive and more ‘slide in’ tasks management, as well as the need for comparison of the initial and ‘adjusted’ planning, automated constraints and alerts and more comprehensive visualization of the task connections.

For their work, U18 mostly relies on Excel for planning and scheduling, and post-its for production management, and outlines that the clear understanding of the paper-based method is essential before development and implementation of digital tools, U19: “*I believe that it really necessary to analyze and understand how it is done [production management] with paper tools, before switching to digital*”. The U19 agrees with the statement, and highlights that the ***real value is in the well-developed, efficient and functional lean construction management system***: “*First [we must] have a functional system, comprehensible for everyone, [we must] know how to manage and manipulate it, and then digitalize it*”.

Despite the lack of required features for 4D production management, U19 sometimes prepares the 4D model for the project meetings with different trades to foster discussions, but the further construction management is not 4D-based. The ***4D printed on paper views become a basis for visualization*** on the Kanban, the work process is focused on ‘post-it’ annotation. Yet, he hopes to be able to rely on it in the future: “*...if we manage to use 4D as the medium for construction management, it would be great*”.

Reporting on the use of the digital touch displays as collaboration mediators, the users outlined their appreciation of touch interactivity, yet they do not consider the large touch displays as relevant mediators, since they have more limited display area than the walls and various display boards. On the

display, they only have “...the view only of the selected weeks but not of all of the project, and this is problematic, but we will never have enough screen space for all the duration of the project.” Therefore, some display limitations are to be considered for the digital Lean boards in the future.

Regarding the need for digital continuity, U19 shares the positive experience from construction management updates *mediated by a centralized platform*, allowing the crews to update task status in real time remotely with the help of the portable tablets connected to the on-line server. According to the user, the control and administration were facilitated by such system, yet it was limited only to the tasks updates. U19 outlines that information management is “for construction management we need details, many details which are up-to-date, but the hardest is to manage the information and this is really the constraint how to have the details and the ease of use”.

Regarding the use of 4D and its joint implementation with Lean construction principles, the experts highlight that it would be certainly beneficial and *would improve communication*. They comment on the proposed prototype “4D simulation and proposed sequence add ‘power’ to the communication”. Yet, they outline that 4D implementation for their production management is not yet possible, and hope that 4D use is going to be useful in the future, for now they see better efficiency with paper-based management. U19 shares that the experience of previous tests of some digital tools was not satisfying, therefore, he prefers: “... to stay on paper, which has the manipulations fast enough, clear enough for everyone, with the information that I must communicate, and it is quickly done, and everyone understands it.”

From the perspective of the *prototype use at pre-construction phase or for the overview* of the progress, both users agreed that the phases schedule level view of the prototype provided relevant and useful visualization of the whole scope of the project. U19 suggests, that in the future the earliest prototype implementation step for a pilot project would be to make the milestones and phases view available with 4D simulation of construction, but to further manage the processes with post-its. The participants also proposed to extend the milestones view and combine it in a way with “large project goals” illustrating the major project phases.

From the perspective of production management, the participants provided *positive feedback on the proposed 4D filters, and possibility to visualize the construction zone and specific trade*. They also suggested further customization options. However, U18 highlights that one of the responsibilities of the construction manager is to guide the trade crews with and to offer them the most efficient and relevant, useful and easy to use tools. Thus, they suggested various improvements to adapt the tool not only to the pre-construction but also to the construction phase. U19 comments that the prototype is “... good, but it's not usable right away for my work”, with some potential to explore and develop further.

First, and the outmost emphasized by the users require for more features to *manage visualization of the ‘granularity’ of schedule level*. User U19 highlighted that usually on a project they have many small tasks and *navigation to the right view of the model would be complicated* after adding all of them to the digital view, thus the view would be complex and would make the model ‘heavy’ thus not easy to interact with.

Furthermore, U19 outlined that on their usual board “... we see all the chain in advance”, which illustrates to the trade crews in an explicit way how their actions and delays impact the project schedule, and the other trades tasks, and all the production chain. He also outlines the importance of clear and visual explanations of reasons for some tasks decisions or needs to finish some tasks first.

Thus, for the U19 “... *the communication tool must show why it is necessary to do the task at the given moment*”, which highlights the importance of the clear visualization, and need to continue the exploration. Therefore, U19 emphasizes the importance of the visualization of the whole project and the tasks in questions at the same time: “*it’s always micro and macro [schedule views] in play and to illustrate why certain measures are necessary*”. The manager highlights that for efficiency of schedule visualization and interactions “*It should be possible to go from macro to micro in one click.*”, but maybe with some macro views staying visible the whole time with the clear indication of the position, and the U18 strongly agrees, and emphasizes the philosophy with: “... *people need to get into the [construction management office] room and see the status of the site right away*”, thus an ideal tool would provide an interface really clear to everyone without a need for detailed explanations or training.

Regarding the tasks related to information and requirements, they highlight an example concerning the *requirements about materials*. They suggest that the information about the materials order and purchase state, as well as the confirmation of the order of the purchase, the delivery date, the stock and storage management would be useful to add to the task. The experts also demanded to be able to customize the maximum task duration according to each planners needs; with their approach they prefer to have the tasks not exceeding one week or two.

This evaluation confirmed the benefits and issues mentioned by the collaboration groups, but most of all emphasized the point of view from Lean construction implementation experience, and provided the ground for the further development.

5.2.2.3 Design and interactions

An aesthetically pleasing design of the interface is very important, since it affects first the users’ perception of the usability, and users are likely to find the application more satisfying to use (Preece et al., 2015). In addition, many AEC professionals have a certain sensitivity to the quality of an image. Also, *modern users are accustomed to quality design solutions* as well, due to the rapid development of UI/UX designs and the broad use of touch-based applications. Thus, it was important for the prototype development and evaluation to gather the users’ feedback on the prototype’s interface design.

The feedback from phase 1 is summarized separately from phase 2, since phase 1 was focused on exploration and limitations identifications, as it is interface also had simplified functions. Further, phase 2 interface was offering the participants, which are referred to as “users” from UCD perspective, already more functions and implemented the users remarks from phase 1.

Computer Usability Satisfaction Questionnaire

First, the CUSQ offered a quantitative summary of the users’ perception of utility, information quality and interface quality, as well as their general satisfaction. The Version 0 evaluations by three groups of total 9 users were aiming to explore the general ideas about the tool use and guide the interface design, they have illustrated that most of the evaluation session participants (users) perceived to some extent the utility of the proposed prototype version and information quality, and mostly pleased by the interface quality and generally satisfied. In more detailed feedback of the first phase by users (Figure 139), U1 and U7 gave the highest scores constantly in every category, they had background in architecture and structure engineering, used 3D for many years but did not use 4D or do project planning or scheduling, their perception was influenced by their experiences. However, these users consider themselves as ‘early adopters’ and quite open to new technologies use.

Moreover, U7 has vast experience of the touch-table use as the meeting mediator. U5 had some experience with planning and 4D, and despite the interface quality, utility and general satisfaction exceeding the score of 5 (from 7), the information quality was noted with 4, highlighting the need for improvements. The lowest scores were issued by U2 with experience in civil engineering, but not in 3D/4D use or planning, the same user only interacted twice with the tool during the session. The scores guided the further development, and their interpretation was combined with other data gathering tools.

The Version 1 evaluations by Group 4 of 2 users who were aiming to explore the use of the tool as a medium during a collaboration with pre-construction sequence review of a design team member and a client scenario, thus the complexity of the tasks and the project were different from the first phase. Figure 140 illustrates the CSUQ score from the Group 4 of U10 and U11 as extremely positive, confirming their positive perception of the four evaluation categories, guiding the further development in the chosen direction. During the collaboration, the discussions and interactions of the users very natural, and productive, they successfully accomplished the proposed collaborative task. Both users had experience with 3D modeling, and U10 was familiar with planning and touch-tables use a medium for the meetings. Yet, both users also added a variety of comments useful for the further prototype development.

The Version 2.1 evaluations by Group 5 of 3 users, who were aiming to explore the use of the tool as a medium during a collaboration with pre-construction sequence review of a design team member, construction team member and a client scenario, thus the complexity of the tasks continued to grow. All the users had rather architectural background, yet some experience as the construction crew members, they also had experience with 3D and planning, yet not familiar with Lean construction. Thus, a part of the session focus shifted from the collaboration task and 4D Lean board use to the Last Planner System concepts and elements exploration. However, the users rapidly finished their collaborative pre-construction task, which illustrates the usefulness of the tool for such tasks. Yet, they unfortunately shifted towards 'construction phase' set of minds and provided the evaluations rather from the production management perspective. Figure 140 illustrates the CSUQ score from Group 5, all the users still evaluated the general satisfaction with 5 points from 7, U13 and U14 gave similar evaluations, of all categories, but U12 provided evaluated information quality and interface quality with 3 points. This group completed the task rapidly and proceeded further towards a discussion and provided a significant number of suggestions and ideas.

The Version 2.2 evaluations by Group 6 of 3 users were aiming to explore the same scenario as well as the previous group. Each user had the most relevant background to the proposed scenario, U15 representing the design team members with the architectural background and experience with 3D and planning, U16 represented the construction team with the background in civil engineering and construction management, but without much of experience in 3D use. None of the users had experience with 4D nor Lean construction. U17 assuring the role of the client at the meeting was the actual client of the reconstruction project proposed by the collaboration scenario, with years of 3D use experience. The users followed the proposed collaboration scenario and accomplished the collaboration task rapidly as well. U16 (construction team) provided the most positive feedback, with the maximum number of points possible for the interface quality and general satisfaction. The most emphasized category by the client was the utility of the tool. U15 (design team) evaluation gave similar score to all the categories. The team achieved the collaboration task, and provided feedback for the interface and collaboration scenarios, with focus on the tool improvements for construction production management, with only few suggestions for the further UI design evolution.

The Version 3 evaluations by Group 7 of 2 users practicing Lean construction as construction managers in a general contractor company. Thus, they have experience with planning, management and some use of 4D. Their inputs were extremely valuable and provided the unique perspective of the production management with lean tools. Thus, for the evaluation they took the perspective of the daily production tasks management, which was not comprised into the prototype, which resulted in rather modest evaluations of utility in comparison with other users, yet in identification of specific and construction management relevant requests for more information. Their feedback on the interface features is still interpreted as relatively satisfying regarding the ‘general satisfaction.’

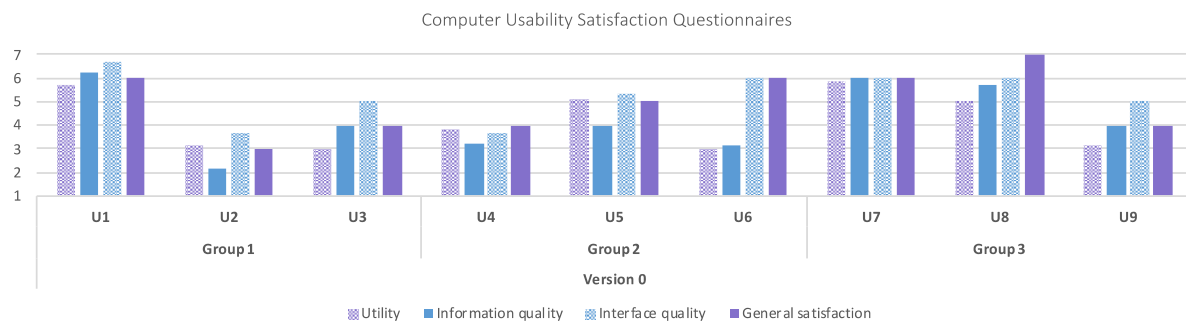


Figure 139 Summary of CUSQ by 4D Lean Board by user Phase 1

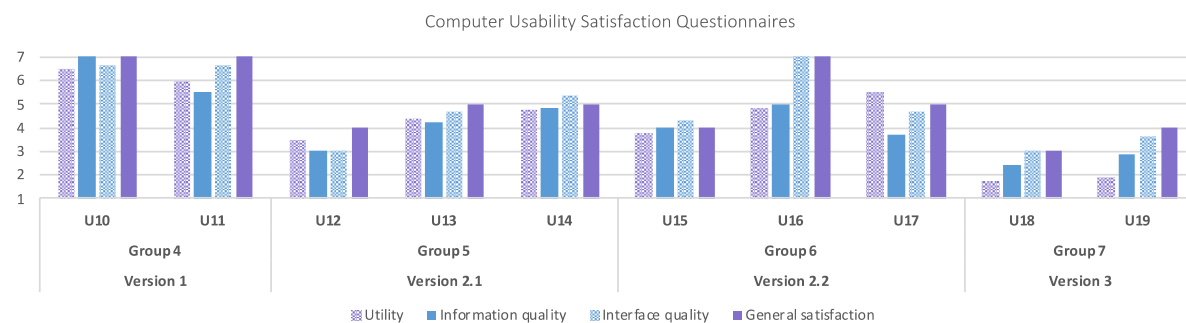


Figure 140 Summary of CUSQ by 4D Lean Board by user and by version for Phase 2

Design-oriented Evaluation of Perceived Usability

Design-oriented Evaluation of Perceived Usability questionnaire was also proposed to the groups, providing feedback in categories: perceived content, perceived information and architecture of the information, navigation perception, perceived ease of cognitive effort, layout pertinence perception, visual guidance; thus, it provided more specific guidance for the iterative design.

The Version 0 evaluations by 9 users were aiming to explore the general ideas about the tool use and guide the interface design. All the categories scored more than 3 points, with the navigation perception being the lowest at 3 points, and layout pertinence, ease of cognitive effort and information architecture perceptions scoring above 3.6 points, thus representing the strongest points of the Version zero, and highlighting the need to improve first navigation and visual guidance.

Figure 141 summarizes the scores by categories and illustrates the similar perception of the tool which influences the scores by user from the previous questionnaire. The colors, represent background/role during the evaluations, with the *blue affiliated to the design team members, green to*

the construction team members, and grey to the clients. Similarly, to the previous responses the users U1 and U7 gave the highest scores, together with the users U5 and U8, and U2 the lowest.

During the following phase of the development the users were aiming to explore the use of the tool as a medium for collaboration at the pre-construction phase to review the proposed by the protocol sequence. The users participated as the design team member, the client, and the construction team members for the versions 2.1 and 2.2. With the prototyping phases advancement, the project complexity augmented but the interface advanced as well.

The Version 1 evaluations by Group 4 of U10 and U11 gave the highest score in every category, as the most satisfied by the prototype design (Figure 142), the observations of the collaboration report not only the easy use of the prototype, but also the ‘interactivity’ of collaboration. The Version 2.1 evaluations by Group 5 highlighted the weakness in the perceived content in information architecture (Figure 142). The Version 2.2 evaluations by Group 6 were more homogenous than the previous group, with all the categories being close to the balance (Figure 142). The Version 3 evaluations by Group 7 were as critique as the previous questionnaire, and had the same limitations of perspective, yet provided insightful feedback on perceived ease of cognitive effort, but revealing need for the more content visualization (Figure 143).

Perceived content pertinence

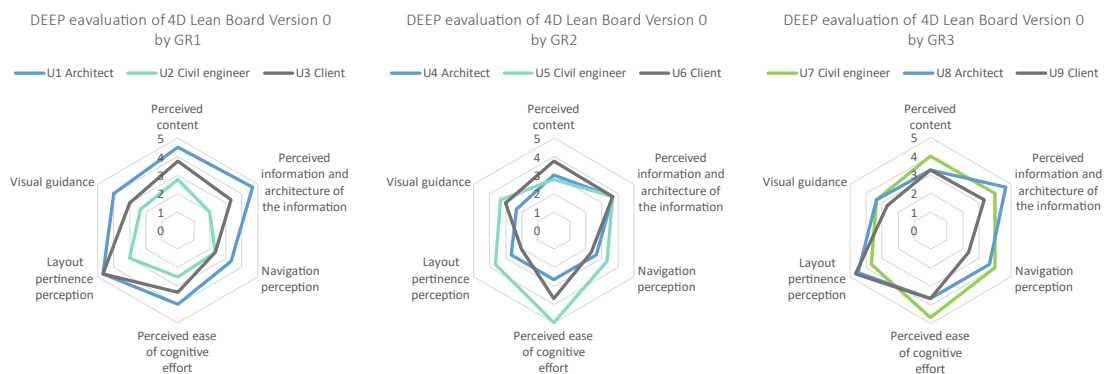


Figure 141 Scores representation of DEEP evaluation of 4D Lean Board prototype version 0 by every member of the collaboration group (blue affiliated to the design team members, green to the construction team members, and grey to the clients)

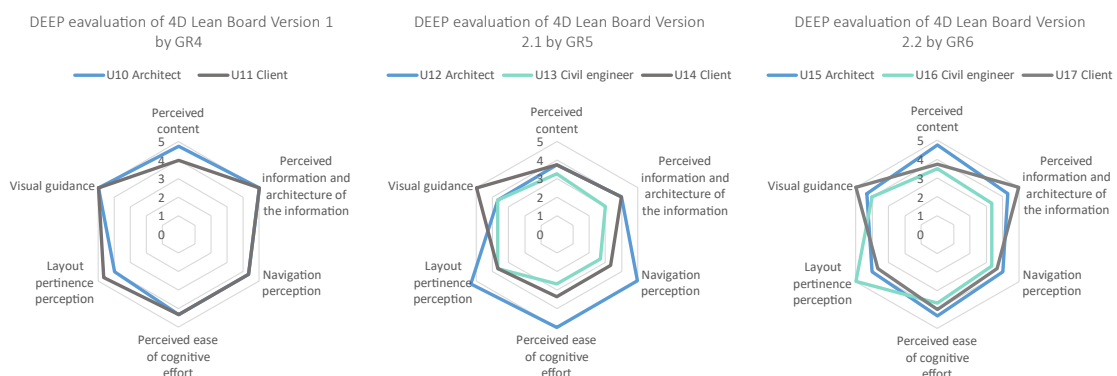


Figure 142 Scores representation of DEEP evaluation of 4D Lean Board prototype versions 1, 2.1, 2.2 by every member of the collaboration group

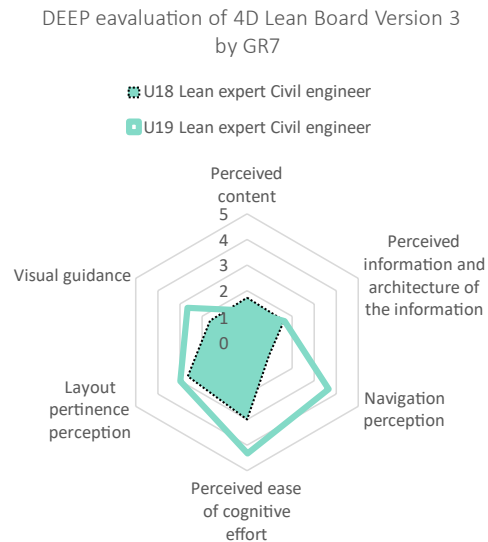


Figure 143 Scores representation of DEEP evaluation of 4D Lean Board prototype version 3 by Lean construction managers

In summary, the quantitative data provided the tools guiding the design progress and tracing the users' feedback in precise categories. Most of the users perceive the design as easy to use and usable, however, the qualitative data provides more complete feedback and allows to gather the insights specific to 4D use and collaboration. It also facilitates the discussion about the identified tendencies.

Interviews and observations

During the Phase 1, despite following the simple collaboration scenario at the evaluations at the first phase, the evaluation participants ***expressed that they have enjoyed the design of 4D Lean Board interface***. They highlight as an advantage the simplicity of the lay-out design and interactions logics. U7 found it to be a: ***“useful tool to manage many aspects”***, for example for ordering the construction materials. Which contributed to the collaboration scenarios and interface functions development.

The participants perceived the ***interface as easy to interact with***, despite the remarks about the small size of some elements. Also, they commented on their perception of an easy access to all the functions without additional manipulations, as well as an easy understanding of the interface lay-out.

The participants mentioned many useful ideas for the labeling of interface. For example, a preference ***to back up the menu's icons of the IFC and schedule levels with text***. They also desired for more expressive feedback ***on the active*** menus and filters of both views, and for the 4D on play. The users also highlighted the importance of the interaction priorities management by the 4D Lean Board, as well as the need to manage the order of interactions during the session. Thus, the interface feedback alerts, which respond to the user's interaction with the 4D model, indicate to the users with the green frame and locks the 4D simulation play after the active user. The participants suggested that a session manager may be in charge, but as we have seen ***during the discussion the interactions come naturally***. But we implemented the system feedback with the touch locks on interactions with the 4D play.

During the Phase 2 the project was not complex, however it illustrated that even with relatively simple projects the information management is essential to decision-making, U12 suggested to ***“... add a research bar, to be able to look up any specific element of the model and highlight it quickly, task or 3D***

element". Further, the users had access to IFC hierarchy with the list of elements. Group 6 found it useful, yet did not consult it, nor the elements information 'on click' for their collaboration.

In every group the participants highlighted that since they are normally able to customize their design visualization and graphics styles, it is important for them to be *able to customize the 3D styles* as well. Therefore, the 4D Lean Board 3D styles customization feature was currently summarized as a table sheet managing the colors, highlights, transparency and edges of the 3D elements and the team colors. This allows to quickly customize the 4D view without any input from the programming team. In the future this feature may become a part of the landing page and with a more user-friendly interface than the table sheet.

In addition to the touch table setting, the users even thought about a possibility to 4D Lean Board on more portable devices, such as smartphones or tablets. This feedback follows the user's remarks on the equipment but emphasizes on the use of the 4D Lean Board. The evaluation participants, even at the first phase, saw the prototype as a *potentially particularly useful for a distant user intervention* or consultation at the collaboration session, for a construction site feedback use scenario.

The Phase 2 evaluation participants were evaluating the more elaborate interface and interactions design with many functions and improvements suggested by the participants of the first phase. Likewise, they have *highlighted their appreciation of the interface design and lay-out*, U10 describing it: "... as appealing and innovative", U11 commenting that "it is cool, and we learn fast how to use it". Most of the users from the Phase 2 even thought that 4D Lean board interface encourages to interact with it.

They also continued to describe it as a simple to understand and not with too many elements, information nor labeling, for example U15 comments that the implementation of the color creates efficient visual aid to distinguish construction teams: "... the 'colored stripes' help with the distinction of the crews and even in 'hidden details' mode provides the status information about the tasks".

One of the most mentioned comments on the *high quality of the 3D model visualization*, as it being appealing and easy to understand. The participants valued plenty the proposed 3D and 4D filters.

5.2.2.4 Prototype evaluation conclusions

In summary, the evaluation aimed for exploration of different aspects of the outlined socio-technical system, concerning:

- *Digital synchronous co-located collaboration;*
- *Digital collaboration environment;*
- *4D BIM and Lean scheduling joint use;*

The users' feedback suggests that they perceive 4D Lean Board as a particularly collaborative tool for a construction planning meeting. They find it useful for the meetings to evaluate the project progress, and certainly interesting for the construction planning.

Digital synchronous co-located collaboration

- *C1. Do participants achieve the goals requested by the evaluation scenario?*

The collaboration scenarios with the goals were proposed to the participants during the second phase of the evaluation, and all the groups succeeded at the tasks that were proposed as potential activities relevant to the goals of collaboration scenarios. The milestones review and phase sequencing scenario was proposed to the Group 4, representing a design team member and a client at pre-

construction phase. The construction schedule and review scenario were proposed to Groups 5 and 6, representing a design team member, construction team member and a client at pre-construction phase. The observations of the groups, as well as their feedback analysis on collaboration suggest that the goals were achieved.

- *C2. What do participants require for efficient collaboration flow: project documentation access, protocol, tools?*

Most of the evaluation participants were French AEC professionals, who pay particular attention to local work practices. They often had various reservations regarding the touch table system cost and mobility, or had concerns about its' usefulness for small projects.

The participants were presented with the 4D simulation of the project represented with a 3D model and milestones, phases, lookahead schedule levels as a medium for collaborative decision-making. Every group of users requested to have access to the Gantt chart schedule and CPM, emphasizing that they are used to work with such kind of schedule representation. Thus, it is essential to provide access to such mediums.

The second most requested type of information was the project's plan, especially by the design team members. Some users suggested that it was essential not only for decision-making but also for the reporting. The proposed feature of the 3D section of the model was perceived as useful, but the users were suggesting the use of interactive 2D documents. Another often mentioned request was task status updates from the construction site, and task-related documents, such as materials order, costs information, crew information, instructions to accomplish the task, pictures confirming the accomplishment, and related to the task decisions in the previous meeting reports. Thus, the requests emphasize the complexity of information related to the task and required by the users. Also, digital core of the project and dataflow continuity would be useful to provide such access and maintain information stability.

Need for collaboration and integration protocols defining the legal frame and responsibilities was also emphasized by the evaluation participants. The approaches of integrated project delivery and BIM-based design could offer the required framework. The participants suggested that a session manager may be in charge, but as we have seen during the discussion the interactions come naturally. They would also like to have an integrated management of the modifications and updates of the project.

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team.*

The evaluation does not disprove the hypothesis; we noted high engagement of the participants in collaboration activities, use of the mediator, dynamic discussions; the participants emphasized their perception of the improvements. The proposed digital environment and prototype system passed the minimum criteria, and allowed to bring improvements to the schedule waste control possible due to the system making potential issues clearly visible. However, to illustrate the real value of the proposal, a long-term study on a real construction project would be necessary to provide the grounds for any conclusions.

Digital collaboration environment

- *DCE1. How do the participants perceive usability and utility of the proposed digital collaboration environment setting for more collaborative decision-making with BIM?*

Multitouch table was the consistent element for all evaluation sessions. The feedback suggests the almost unanimous positive perception of the utility of the table. The setup including the vertical screen was not perceived as a necessary or helpful by the half of participants, regardless of the evaluations phase. Most of the participants noted that it was very pleasant to use the multitouch table. The table's size seems to be right for a small meeting of a group of 3 to 7 people. The large size of the digital project documents and the possibility of 'zoom in' or 'scale' guarantees a high visualization quality. The users noted the utility of BIM model for their decision-making as well.

- *DCE2. Does the proposed setting allow more equal access to the project information to all the participants during the meeting?*

During the second phase, all the participants enthusiastically interacted with the proposed 4D BIM simulation and used it as a medium for project exploration and discussion, regardless their background, knowledge of BIM, planning or Lean construction. The participants also indicated that in the given short time of the session they quickly understood how to interact with the tool; it seemed intuitive. They highlighted the ease of use of the touch table and the prototype's interface. That effect is also illustrated by the results of the questionnaires. However, some of the participants would prefer to try the same application at a meeting with individual small tablets, since they are used to using individual tablets for construction site visits and follow ups.

- *DCE3. Do users achieve the intended interactions?*

The observations of the evaluation sessions and users feedback allowed to integrate the noted missing or suboptimal interactions into the development. Most of the time users do achieve the intended interactions with the versions 2.1 and 2.2 of the prototypes. However, some design adaptations are necessary to the precision of the touch gesture on the large screen and 'interface feedback' about the interaction, as well as the development of the requested features.

- *H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration.*

The results of our evaluation comply with the proposed hypothesis. Further evaluation to investigate the subject would involve implementation of nD visualization for real project meetings, and evaluation of the natural user interactions in a long-term study. Moreover, the evaluation emphasizes the requirements and needs for the future improvements.

4D BIM and Lean scheduling joint use

- *D1. How do participants perceive the use and usefulness of 4D Lean Board for their professional practice?*

4D visualization, interactions and schedule adjustments are the core purposes and functions of the prototype. Most of the participants had never had any experience with lean project management nor have been familiar with its concept. Yet, their feedback and survey answers outline the perceived usability and perceived usefulness of the prototype main features. However, further development, extension of the functions and options adapted to production management, and customization to the specific team needs are necessary.

- *D2. Do users understand the 3D, schedule levels and 4D link visualization of 4D Lean Board?*

According to the participants' feedback, it was a great visual aid to use the 3D model and the schedule connected with the 4D link to understand the project well and quickly. An easy gesture of the cursor movement on the timeline or task weeks was perceived by the participants as an efficient way to navigate the 4D simulation. The feedback on the suggested filters, camera movements and 4D link highlights was mostly positive. The architects were the most active users of the filters and 3D navigation, as well as of the phase level view. The usefulness of the 4D filter by teams was highlighted by the participants who were most accustomed with the construction scheduling. The distinct roles, such as architect, client, engineer or construction specialist were observable in feedback.

The observations and the evaluation tasks achievement support the expressed feedback. However, the participants expressed some concerns about the need to remember the order of the task requirements to understand the summarized view of the checked and unchecked requirements on the sticky note.

- *D3. Do participants achieve collaboration tasks proposed by the evaluation protocol?*

The evaluation tasks were designed to observe the collaboration interactions and relevance of the proposed medium. Groups 5 and 6 representing a design team member, construction team member and a client at pre-construction phase also performed a review of the project milestones and evaluated the construction phase sequence, propose the sequence optimization if possible. They were also asked to examine the lookahead schedule for any issues such as issues in the assigned task order or duration, and to propose their optimization. Group 7 also examined the tasks and modified the schedule if necessary. The proposed evaluation tasks were mostly achieved without assistance or requests for information, and in a relatively short time.

- *H3. A digital tool uniting BIM 4D and Lean scheduling creates a basis for the integration of design and construction dataflows, and is perceived by the users as providing a relevant level of information detail for collective decision-making at every phase.*

4D Lean Board prototype was perceived by the users as a medium enabling clear visualization and intuitive interactions with the project model and construction schedule united with the 4D link. They also noted the useful potential for digital dataflow, interactive collaboration and construction management. However, future development is required to overcome the prototype limitations.

Limitations and research perspectives

The user-centered design approach guided our iterative design and development of the prototype allowing for a rapid development of a usable application prototype and concepts validation, but as any approach it has its own limitations. Since the approach puts the user in the core of development, the user's feedback influences the development steps, but also represents the source of bias. Yet, the UCD approach and evaluation methods focus on the perception of efficiency and usability from the perspective of a user experience, and do not seek to provide general conclusions. Another aspect of the approach limitation is the iterative nature of the design development, which did not seek to provide multiple evaluations of each version of the prototype by a large number of users.

Since our approach to collaboration study encompassed the collaboration group persona, and not the individual users, it was essential to gather feedback from a group of users working together on the same tasks during the evaluation and bringing their expertise from different backgrounds and perspectives. These groups were not constant, and changed at every evaluation session, thus the users did not have time to forge long-term collaboration bonds, unlike the students from the experiments, influencing their social reflexivity. However, all the groups achieved the collaboration tasks and used

their professional expertise to do so, which is very similar to the early stages of the project team social functioning.

Digital synchronous co-located collaboration extending to distant collaboration: since many of the 4D Lean Board evaluation participants have expressed their vision of the use of the tool for construction progress management, they naturally included the request to be able to do not only co-located decision-making, but also a distant one. They imagined a *possibility to request information directly from someone on the construction site* and display it on the table or the screen.

Digital collaboration environment supporting all kinds of mediums and gadgets. In addition, the development of synchronous distant collaboration tools and methods has been boosted by the need due to the global pandemic of COVID-19. Therefore, many AEC professionals had to adapt to the new tools and invent new ways of collaboration. With the perspective of such changes, it is likely that the digital collaboration solutions would adapt to the users' needs. Thus, shared information visualization and group interactions should be also adapted to the specifics of distant collaboration.

4D BIM and Lean use for design, construction and operations. From the construction scheduling and production management perspective there is a limitation to the task survey since one of the prototype limitations is the lack of features enabling various types of inter-task dependencies, such as “start X when Y starts” or “end X when Y ends” were not covered by our schedule management architecture.

Due to the limited development time, the collaboration tasks were mainly focused on visualization and identification of schedule errors, simple tasks order modifications, and not on collaborative schedule development. Thus, various useful time management tools and Lean Construction tools were not implemented. However, the data architecture of the application is designed to allow simple implementation of additional features.

The prototyping was focused on the use of 4D Lean Board at mostly pre-construction and early construction phases, with possible extension to design and full-scale production management phases. Regarding its qualities as an interactive board for the building information visualization and possibility to assign tasks or activities to the 3D elements, in the future it could evolve into a tool also suitable for operation and maintenance visualizing a digital twin of the delivered project.

Despite the fact that most of the users did not have experience with Lean Construction, their feedback on the prototype usability and required features was very valuable, illustrating the point of view of a professional who must understand rapidly the new project and the new Lean scheduling method at the project meeting, and to work with the other disciplines on the collaboration tasks while providing his professional expertise. However, the Lean experts evaluation allowed to assess the requirements for the future development including customization possibilities, additional tools, features and views which are essential for construction production management.

Design and interactions improvements and updates. From the user interface perspective, such an important aspect of a quality interface as the *accessibility*, which is defined as “a degree to which an interactive product is accessible by as many people as possible” (Preece et al., 2015), was not in the scope of our design and prototyping in order to simplify development, and the prototyping result was not aiming to develop 4D Lean Board as a product for a targeted group nor fully ready for a commercial release. Therefore, more detailed study accounting for the users with vision limitations, or touch—interactions would be relevant to overcome possible issues.

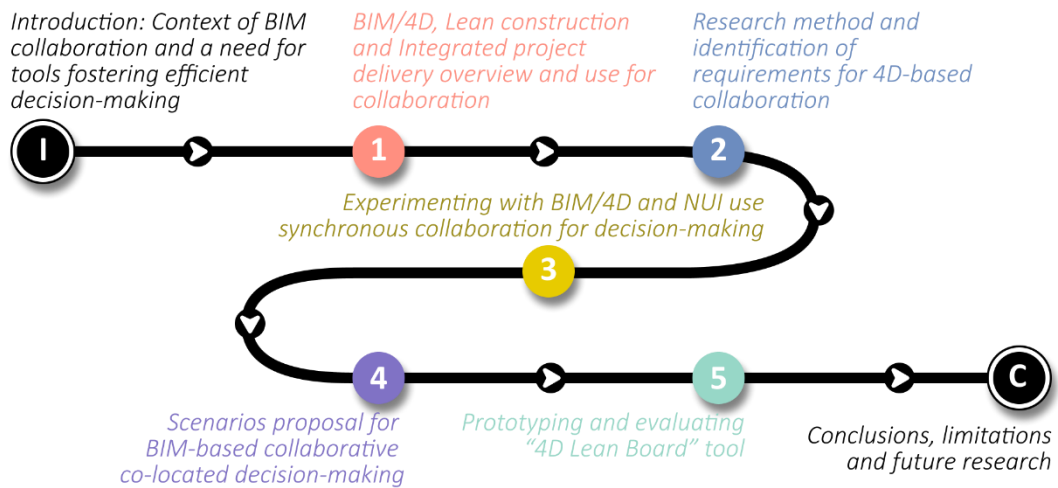
Summary of Chapter 5

Prototyping and evaluating “4D Lean Board” tool

- The association with research context of 4DCollab project research project, allowed us to benefit from the expertise of the multidisciplinary research team. While both studies shared similar goals, surveys and experiments results, the prototyping results focus on different elements of collaboration process, since we explored the Lean schedule visualization.
- 4D Lean Board prototype development and evaluations were structured with categories addressing different levels of STS: digital synchronous co-located collaboration; digital collaboration environment; 4D BIM and Lean use; design and interactions evaluations.
- According to the users’ feedback and observations, the digital collaboration environment with a medium enabling quality 3D visualization and natural interactions interface was perceived by the users as useful and efficient way to improve collaboration. Digital synchronous co-located collaboration was more interactive and engaging as well.
- BIM 4D and Lean scheduling joint implementation presented the AEC professionals not only with the efficient visualization as a medium for collaboration, but as a tool for more engaged and interactive collaboration. Lean levels of schedule and task requirements were perceived as efficient tools to communicate the project planning, and as efficient for construction management.

Conclusions

This section emphasizes the general conclusions of our research, by presenting a summary of the problematics and our research approach, it outlines the results and the presented proposals, and it concludes with the limitations and perspectives for future research.



Conclusions

Following our research *aim to improve the collaboration quality for AEC professionals* and need to enable *possibility benefit from the advancements in BIM/4D, Lean Construction and IPD approaches*. A synergy of these innovative approaches is foreseeable and important but complex. Thus, their implementation presents challenges due to their novelty, complexity and need for the development of relevant regulations, processes, practices, and tools. Therefore, *with collaboration efficiency as the core and uniting requirement, our research seeks for the ways to foster the development of relevant and efficient digital collaboration tools and processes*.

Thus, the emergence of new tools, as any innovation, aspires for novel uses providing solutions to the existing issues or offers the new functionalities. In addition to the various benefits for a project, an efficient BIM implementation requires digital information continuity, interoperability to support collaborative design and to avoid data losses, to maintain relevant workflows, and the protocols to organize work and collaboration, as well as it requires development of new skills by AEC professionals. With BIM, Lean Construction and Integrated Project Delivery approaches the teams, technology, and processes are integrated into a holistic organization and focused on a shared goal (1.3). The following barriers emphasized from the literature review and the experiments feedback were guiding the research:

- *Barrier 1 (B1). Limited BIM and 4D use for decision-making and co-located synchronous collaboration.*
- *Barrier 2 (B2). Need for efficient time management and integrated collaboration, with continuous data and workflow, relevant data visualization and interactions.*
- *Barrier 3 (B3). Lack of synergy in approaches; Lean construction tools have not yet fully emerged with BIM to enable digital collaboration for an integrated team.*

The research approach relied on a framework combining *Socio-technical systems theory, Activity theory and User-centered design concepts*, tools, and methods. Their combination was used to describe the collaboration context and investigate the usage of digital tools. Therefore, the research considers not only the AEC domain specific elements, but it also converges with the domain of Human Computer Interaction and User-centered design.

The Socio-technical system assisted with general outline of the social and technical interactions of the complex context of collective and more integrated use of BIM and digital tools as the core of collaborative work on a project. It corresponds to the macro “social” level of the conceptualization in our study, which encompasses the collaboration context.

The Activity theory further allowed to emphasize collaboration activities, to encompass actors, collaboration, activity mediators tools, rules, teams and the context into a model. Which corresponds to the mezzo level encompassing the activities in the context of “technical” and “social” subsystems interactions describes *the collective activities and mediators use*.

The User-centered design enabled implementation of the design methods of fostering usability, effectiveness, efficiency and usability aspects of the development of collaboration tools and scenarios. Which corresponds to the micro “technical” level which focuses on *the specifications for visualization and interaction for 4D and Lean collective use*.

Three main hypotheses, corresponding to the levels were evaluated:

- *H1. Co-located synchronous digital collaboration for decision-making would be perceived by the project team members as enhancing collaboration and integration of the team (macro level).*

- H2. The use of a digital medium with quality nD visualization and a natural interaction interface for collective decision-making would be perceived by the project team members as useful for collaboration (mezzo level).
- H3. A digital tool uniting BIM 4D and Lean scheduling creates a basis for the integration of design and construction dataflows and is perceived by the users as providing a relevant level of information detail for collective decision-making at every phase. (micro level).

In summary, driven by the aim and barriers, and based on the literature review, experiments and prototype evaluations, the main results of the study are (Figure 144):

- R1. Summary of BIM and 4D uses, collaborative lean scheduling requirements;
- R2. Summary of collaboration types and group user persona proposal;
- R3. Proposal of collaboration scenarios for 4D BIM based collaboration,
- R4. 4D Lean board prototype and summary of prototype users' evaluations.

Moreover, the proposed research framework encompassing the three levels of digital collaboration study could be considered as one of the main results as well.

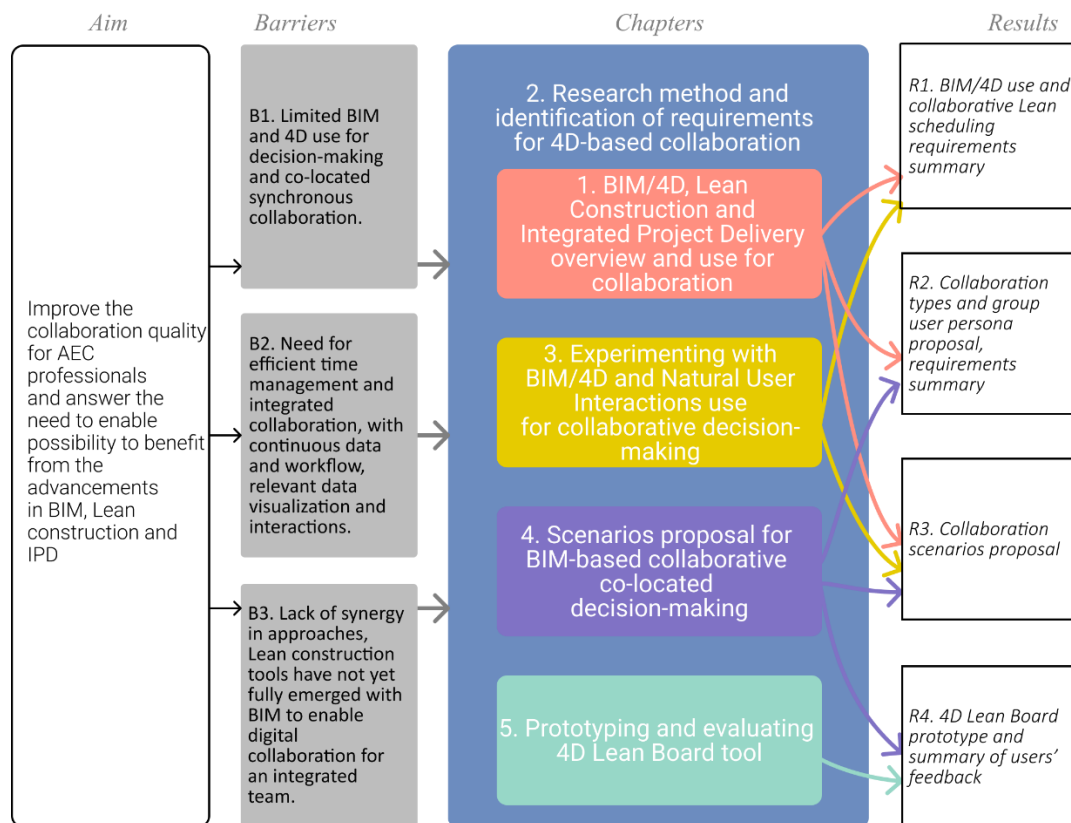


Figure 144 Summary of research barriers and chapters and results

The research approach allowed to study and emphasize the current advancements and challenges brought by the shift of paradigms by BIM, Lean construction and IPD, as well as their synergetic implementation (R1). In addition to the various benefits for a project, efficient BIM implementation requires:

- digital information continuity,
- interoperability to support collaborative design and avoid data losses,
- relevant workflows and protocols to organize the work and collaboration,
- development of new skills by AEC professionals.

Moreover, Lean Construction development and implementation brought a variety of benefits offering responses to the need for:

- *more efficient planning,*
- *process location-based scheduling,*
- *Lean construction waste (muda) control.*

With such approaches, teams, technology, and processes may be integrated into a holistic organization and focused on a shared goal. The results also emphasize the requirements for BIM and Lean collaboration tools on the different levels (R1):

- *Social: transformation of processes, organization and roles:*
 - *Need for practices and approaches relevant to the digital and integrated practices;*
 - *Need for digital data continuity, accessibility and interoperability;*
- *Technical and social: digital collaboration environment setting:*
 - *Need to enhance BIM and digital supports use for collective decision-making*
 - *Need to enhance interactivity, communication and mediators for collective use;*
- *Technical: BIM/4D and Lean planning use for collaboration:*
 - *Need for relevant visualization and interactions for 4D collective use at the meetings;*
 - *Need for relevant for collaboration 4D and Lean planning too.*

4D BIM has a variety of uses, and it represents a *useful medium not only for project design, but for construction simulations, analysis, management, and decision-making* at any project phase. *Lean construction* development and implementation brought a variety of benefits offering *responses to the need for more efficient planning, for process location-based scheduling, and for waste control.*

The results emphasize the digitally based multidisciplinary collaboration experiments feedback, following the aim is to improve the collaboration quality for AEC professionals. We studied the use of digital mediums in the context of small-scale timber construction projects, the users' interactions with digital collaboration table and the project documents.

The results propose *collaboration group personas (R2) and collaboration scenarios (R3) use to describe the collaboration activities (R2, R3), and the prototype of 4D Lean Board (R4).* 4D Lean Board prototype development and evaluations were structured in a way addressing the different levels of our research approach, resulting in following:

- *Digital synchronous co-located collaboration was more interactive and engaging according to the analysis of users' feedback.*
- *The digital collaboration environment with a medium enabling quality 3D visualization and natural interactions interface was perceived by the users as useful and efficient way to improve collaboration .*
- *BIM 4D and Lean scheduling joint implementation was perceived as an efficient project data visualization medium for multidisciplinary and more interactive collaboration. The Lean schedule levels and task requirements were perceived as efficient tools to communicate the project planning, and as efficient for construction management.*

In summary, the research results emphasize the importance of the co-located collaboration improving team integration, engaging dialogues, creativity and interactions aiming to improve project quality (H1); As well as the importance of the digital mediums use for collaboration, which were perceived as enhancing visualization quality and interactivity with natural interactions interface (H2). Moreover, the joint use of BIM 4D and Lean scheduling provided better visualization of the construction process, and became a digital core for efficient and interactive collaboration (H3).

Limitations

Natural every research is limited first by its own aims and specific focus, by the chosen data collection methods, by the collected data. Therefore, we acknowledge our research methodology was guided by the broad aim of collaboration improvement in the broad context of BIM, Lean construction and IPD approaches synergy emergence. Such aim and resulting objectives may be ***narrowed to the study of each approach separately*** or to a study of design team and construction team collaboration interactions.

The mixed data collection methods allowed to gather quantitative and qualitative data and summarize the participants feedback about the digitally based collaboration processes, the use of the digital collaboration environment and 4D BIM and Lean scheduling. The ***data sample size for the pedagogical experiment and for the prototype evaluation*** was typical for AEC research, but small in comparison to sociological and epistemological studies. The collected data samples were not large enough for conclusive statistical analysis, and future research including results from a larger number of qualitative surveys would allow to run more exhaustive statistical analysis. Yet, both qualitative and quantitative data results illustrate feedback consistency and correspond to the aspects found in the literature review.

The pedagogical experiment allowed to survey multidisciplinary collaboration and digitally mediated project review meetings preparing the construction of the small-scale timber projects. Thus, it provided a context to observe a close to the real project development work and issues. However, the ***main population of the experiment represented by students***, did not have significant experience in collaboration, collective design, digital tools use for design and for decision-making, nor in construction. Therefore, the feedback summary identified that participants with experience do not provide the same feedback as participants without. Despite the evaluation of the projects from the program phase to the real delivery, the students were still not fully responsible for the project outcomes, therefore their feedback is biased by such responsibility limitation.

The user-centered design including evaluations of every version of the 4D Lean Board prototype did not allow to gather a great amount of data concerning the last version of the prototype, and additional ***evaluations with greater number of participants*** could prove to be beneficial for more precise outline of the user needs. The prototype evaluations had the real project data and related tasks as the project content for collaboration scenario, yet the evaluations were conducted in a controlled environment. A further evaluation of the ***prototype implementation in real scale project*** would be beneficial. Moreover, various evaluations with different types of real projects may be beneficial as well.

The limited time of prototype development did ***not allow to develop all the necessary features for construction production management***, and the activity level of the Lean schedule. Further evaluations and user-centered design with construction management and Lean construction experts would help to overcome such limitation.

In addition to these basic limitations, our research was conducted with ***participants from the French and Luxembourg AEC professional and cultural context***, thus had a strong regional focus, which impacts the feedback results as well. For example, many of the participants did not use BIM for collaborative design or value engineering, most did not have experience with Lean construction or Integrated Project Delivery.

Future research

The 4D BIM uses allowed to investigate the complex project information visualization and interactions requirements, and consider the large context of BIM-based, more integrated and collaborative project delivery. However, not only the time and resources management is essential for efficient decision-making at any project phase, including program and design phases, but ***also the costs information*** (5D BIM). 5D allows to consider financial implications of the design choices at the program and design phases (Marin et al., 2015); as well as construction management choices at pre-construction and construction, while linking the model, the activities and the costs (Vigneault et al., 2020). The experiments participants emphasized that costs information is essential for them for construction planning and monitoring, and suggested to add it to the proposed tool. Therefore, one of the directions for the further exploration of collective use may explore the use of 3D, 4D and 5D BIM for collective co-located decision-making at pre-construction and construction phases. Such direction would allow to explore the technical requirements and implement the UCD tools within the micro level of our research approach.

Not only the co-located but also remote, and hybrid collaboration tools become essential to the work practices, fostered by the technological progress, the augmented data transfer speeds and recent popularization of remote work. Therefore, further research should consider how remote collaboration devices may provide useful input for co-located meetings, either by connecting two different teams, or ***reaching out directly to the construction crews on site***, while staying at the office, but sharing the same digital core for collaboration. Feedback from the AEC professionals emphasized a potential scenario of such use for more informed decision-making, for pushing and pulling the schedule tasks, and for construction monitoring. Such explorations would contribute to the collaboration activity study at the mezzo level of our research approach, and potentially extend the list of the technical and social requirements.

Exploration of other technological solutions than the touchscreens for visualization of complex project data and allowing for interactive collaborative decision-making was requested by the prototype evaluation participants. They suggested to explore usefulness and effectiveness ***of the personal tablets*** visualizing the same model, and being a ***“mobile” medium available to the project team members*** at any time. Moreover, various studies explore the use of ***virtual collaboration environments*** as a tool for collective design and project review, using VR headsets (Chowdhury and Hanegraaf, 2022) or immersive environments with 360 displays (Dorta et al., 2016; Kassem et al., 2017). Various studies investigate the uses of Augmented reality in AEC (Soman and Whyte, 2017; ; Ratajczak et al., 2019), and they often consider the on-site control. However, AR could be also implemented to mediate the project meetings.

As one of the potential technological solutions to test, there may be a benefit from the use of ***augmented (mixed) reality headsets like HoloLens at the meetings*** (Khan et al., 2021). This would enable visualization of a project BIM model and 4D BIM simulations animations not only on the 2D screen but in 3D space, as well as the possibility to switch between a scale model view and a 1:1 scale visualization of the project to investigate design in detail. Such visualizations are available for a group of people. The gestures and interactions with the virtual contents seek to be as natural, as the physical world gestures such as navigation in the physical space and pointing, which would be natural to the users.

Furthermore, Lean construction on-site control and updates are possible not only with the manual updates, but benefit from ***the automated updates managed through the Internet of Things*** (Dave et al., 2016; Guerriero et al., 2018).

Regarding the perspectives of digital tools future in AEC, the latest developments propose to find common ground for *nD BIM and Digital Twin synergy* (Boje, Guerriero, et al., 2020), which would be encompassing a variety of data types from the virtual models and the real-world data sources, and would have the data extent of significant complexity. Such complexity would *require for dynamic visualization of operational building data in BIM models* to enhance the Human-Data Interaction and implementation of Digital Twins, and like with the 3D or 4D BIM would require for end-user adapted information visualization (Relekar et al., 2021). Moreover, Digital twins provide a possibility to benefit from and store complex data (Hosamo et al., 2022).

Demolition activities are often a part of some projects, but with the emerging development of research on *circular economy in AEC*, the *perception of the construction waste is shifting to its assessment as a resource*. Construction and deconstruction processes share some similarities, and there is a potential for *4D BIM simulations use not only for construction but also for deconstruction*. Such use would foster control of the activities, preservation of the materials and building elements, preparing the available elements BIM inventory for the future projects. Durmisevic et al. already consider the creation of Digital Deconstruction Platform to assist with mediation of collective decision-making for Deconstruction and Reuse strategies of the existing buildings (Durmisevic et al., 2021). The digitalization of the reuse process should help to reveal the highest value of the resources (Lebossé et al., 2022). Thus, with the development of such approaches, the collaboration activities would encompass not only construction or reconstruction but also the deconstruction and reuse of resources, and still require efficient visualization and interaction mediums.

In addition to our research aim, the pedagogical experiment allowed to observe some potential for the future research as well. The future pedagogical strategy must include the *development of digital collaboration culture* (Bolshakova, Halin, et al., 2020). The pedagogical experiments revealed the need and request to enhance digital tools use by the future AEC professionals. This could be done with a curriculum including courses *teaching various disciplines to communicate, share and collaborate, and implementing the digital tools for collaboration*. Such approach would allow to provide the young professionals with the necessary skills and foster the evolution of AEC practices. It would also follow the need to reevaluate Digital education for architects and engineers to integrate more topics and combine the professional disciplines with BIM and Computational Design (de Boissieu and Deutsch, 2022). The digital technology adoption was expected to occur through the younger generations, who are considered to be naturally digitally fluent, yet the experience and understanding of the construction activities are important to acquire before the technological tools studies (Puolitaival and Kiroff, 2021).

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Abbreviations

| | |
|-----|---|
| 4D | 4 Dimensional |
| AEC | The Architecture, Engineering and Construction industry |
| AIA | The American Institute of Architects |
| AR | Augmented reality |
| AT | Activity Theory |
| BIM | Building information modeling/management |
| CAD | Computer Aided Design |
| CPM | Critical Path Method |
| DCS | Digital Collaboration Session |
| DCT | Digital Collaboration Table |
| GUI | Graphical User Interfaces |
| HCI | Human-Computer Interactions |
| IFC | Industry Foundation Classes |
| IPD | Integrated Project Delivery |
| LC | Lean Construction |
| LPS | Last Planner System |
| nD | n Dimensional |
| NUI | Natural User Interactions |
| PPC | Planned percent complete (see |
| STS | Socio-Technical System |
| SUS | System Usability Scale |
| UCD | User-Centered Design |
| VDC | Virtual Construction Environment |
| VR | Virtual Reality |
| WBS | Work Breakdown Structure |

Appendix A

Usability assessment questionnaires

Table 34 SUS items list in English and French

| N | English | French |
|----|--|--|
| 1 | I think that I would like to use this system frequently. | Je pense que j'aimerais utiliser ce système fréquemment. |
| 2 | I found the system unnecessarily complex. | J'ai trouvé ce système inutilement complexe. |
| 3 | I thought the system was easy to use. | J'ai trouvé ce système facile à utiliser. |
| 4 | I think that I would need the support of a technical person to be able to use this system. | Je pense que j'aurais besoin d'un support technique pour être capable d'utiliser ce système. |
| 5 | I found the various functions in this system were well integrated. | J'ai trouvé que les différentes fonctions de ce système étaient bien intégrées. |
| 6 | I thought there was too much inconsistency in this system. | J'ai trouvé qu'il y avait trop d'incohérence dans ce système. |
| 7 | I would imagine that most people would learn to use this system very quickly. | Je suppose que la plupart des gens apprendraient très rapidement à utiliser ce système. |
| 8 | I found the system very awkward to use. | J'ai trouvé ce système très contraignant à utiliser. |
| 9 | I felt very confident using the system. | Je me suis senti(e) très confiant(e) en utilisant ce système. |
| 10 | I needed to learn a lot of things before I could get going with this system. | J'ai dû apprendre beaucoup de choses avant de me sentir familiarisé(e) avec ce système. |

Table 35 Open end questions

| Open end questions |
|--|
| What other problems have I encountered with the interactive table? |
| What is my worst experience with the interactive table? |
| What is my best experience with the interactive table? |
| What are the other positive points of the table? |
| What is my opinion on the association of 3D with the table? |
| The interactive table improves the understanding of project design issues |
| The interactive table does not benefit project review meetings |
| The 3D on the table does not provide a better understanding of project design issues |
| The project review on the interactive table is more efficient |
| The interactive table allows a better visualization of 2D documents than traditional meetings |
| The interactive table allows a better visualization of 3D documents than traditional meetings |
| The interactive table allows a better visualization of 4D documents than traditional meetings |
| I think that Shariing allows to achieve a good restitution of a decision taken collectively. |
| Opinion 4D + Table There were the meetings with the interactive table for the project and for the Wood Challenges. |
| Did you notice any differences in your preparations for the meetings and in the interactions during them? |
| What is it that you would like to automate in turn collaborative meetings and decision-making? (e.g., before the meeting to prepare or afterwards to distribute tasks, or during the meeting...) |
| 3D improves the understanding of project engineering issues. |
| Generally, I do not see the point of collective planning meetings. |
| Shariing software on interactive tabletop improves planning meetings. |
| 4D improves the understanding of planning problems. |
| 4D improves collaborative decision-making. |

Table 36 Reflexivity scale questions in English and French according to Facchin (Facchin et al., 2006)

| | Question in English | Question in French |
|---------------------------|---|--|
| Task reflexivity | The team often reviews its objectives | Notre groupe revoit souvent ses objectifs |
| | The methods used by the team to get the job done are often discussed | Notre groupe discute souvent ses méthodes de travail |
| | We regularly discuss whether the team is working effectively together | Nous discutons régulièrement de l'efficacité du travail de notre groupe |
| | In this team, we modify our objectives in the light of changing circumstances | Dans notre groupe, nous modifions nos objectifs en fonction des changements de circonstances |
| | Team strategies are rarely changed | Les stratégies de notre groupe sont rarement changées |
| | How well we communicate information is often discussed | Nous évaluons souvent la manière dont l'information est communiquée |
| Social reflexivity | This team often reviews its approach to getting the job done | Notre groupe revoit souvent sa manière d'effectuer le travail |
| | The way decisions are made in this team is rarely altered | Nous changeons rarement les procédures de prise de décisions dans notre groupe |
| | Team members provide each other with support when times are difficult | Les membres de notre groupe se soutiennent dans les moments difficiles |
| | When things at work are stressful, the team is not supportive | Quand le travail est stressant, notre groupe n'apporte pas beaucoup de soutien |
| | Conflicts tends to linger in this team | Les conflits ont tendance à traîner en longueur dans notre groupe |
| | People in this team often teach each other new skills | Les membres de notre groupe apprennent souvent de nouvelles capacités aux autres membres |
| | Conflicts are constructively dealt with in this team | Les conflits sont traités de manière constructive dans notre groupe |
| | When things at work are stressful, we pull together as a team | Quand le travail est stressant, notre groupe reste soudé |
| | Team members are often unfriendly | Les membres de notre groupe sont souvent désagréables |
| | People in this team are slow to resolve arguments | Les membres de notre groupe sont lents à résoudre les conflits |

Table 37 CUSQ items

| Computer Usability Satisfaction Questionnaires | Strongly Disagree/ Totally Agree | | | | | | | N/A |
|---|-------------------------------------|---|---|---|---|---|---|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | |
| 1. In general, I find this system easy to use | | | | | | | | |
| 2. This system is easy to use. | | | | | | | | |
| 3. I can do my work efficiently using this system. | | | | | | | | |
| 4. I am able to get my work done quickly using this system. | | | | | | | | |
| 5. I am able to do my work efficiently using this system. | | | | | | | | |
| 6. I am comfortable using this system | | | | | | | | |
| 7. It was easy to learn to use this system. | | | | | | | | |
| 8. I believe I quickly became productive using this system. | | | | | | | | |
| 9. The error messages generated by the system clearly explain how to solve issues. | | | | | | | | |
| 10. When I make a mistake using the system, I can catch them easily and quickly. | | | | | | | | |
| 11. The information (such as online help, on-screen messages, and other documentation) provided with the system is clear. | | | | | | | | |
| 12. It is easy to find the information I need. | | | | | | | | |
| 13. The information provided with the system is easy to understand. | | | | | | | | |
| 14. The information is effective in helping me do my job. | | | | | | | | |
| 15. The organization of the information on the system's screens is clear. | | | | | | | | |
| 16. The interface of this system is pleasant | | | | | | | | |
| 17. I enjoy using the interface of this system. | | | | | | | | |
| 18. This system has all the features and capabilities I expect. | | | | | | | | |
| 19. Overall, I am satisfied with this system. | | | | | | | | |

Table 38 DEEP items

| Design-oriented Evaluation of Perceived Usability | Strongly Disagree/ Totally Agree | | | | | /A |
|---|-------------------------------------|---|---|---|---|----|
| | 1 | 2 | 3 | 4 | 5 | |
| 1. The labeling of the text was clear. | | | | | | |
| 2. Content (text, images, sounds, videos, etc.) was easy to understand. | | | | | | |
| 3. The text was useful. | | | | | | |
| 4. The text was relevant. | | | | | | |
| 5. I could quickly learn the application structure by browsing its basic interface. | | | | | | |
| 6. The application organization was clear. | | | | | | |
| 7. In each application section, the pages were well organized. | | | | | | |
| 8. It was easy to find the information I needed on the application. | | | | | | |
| 9. The application helped me find what I was looking to do. | | | | | | |
| 10. I got what I expected when I clicked on the app items | | | | | | |
| 11. Using the app was effortless. | | | | | | |
| 12. Using the application made me tired. | | | | | | |
| 13. I learned to use the app quickly. | | | | | | |
| 14. The layout throughout the app was consistent. | | | | | | |
| 15. I noticed sudden layout changes throughout the app. | | | | | | |
| 16. The layout of each application section was consistent. | | | | | | |
| 17. The colors helped me distinguish the different application sections | | | | | | |
| 18. The highlighted areas on the interface helped me locate the information I needed. | | | | | | |
| 19. I learned about the interface content by browsing the highlighted areas | | | | | | |

Table 39 TAM3 items from (Venkatesh and Bala, 2008)

| Constructs | Items ^a |
|--|--|
| Perceived Usefulness (PU) | PU1 Using the system improves my performance in my job. |
| | PU2 Using the system in my job increases my productivity. |
| | PU3 Using the system enhances my effectiveness in my job. |
| | PU4 I find the system to be useful in my job. |
| Perceived Ease of Use (PEOU) | PEOU1 My interaction with the system is clear and understandable. |
| | PEOU2 Interacting with the system does not require a lot of my mental effort. |
| | PEOU3 I find the system to be easy to use. |
| | PEOU4 I find it easy to get the system to do what I want it to do. |
| Computer Self-Efficacy (CSE) | CSE1 I could complete the job using a software package . . . |
| | CSE2 . . . if there was no one around to tell me what to do as I go. |
| | CSE3 . . . if I had just the built-in help facility for assistance. |
| | CSE4 . . . if someone showed me how to do it first. |
| Perceptions of External Control (PEC) | PEC1 . . . if I had used similar packages before this one to do the same job. |
| | PEC2 I have control over using the system. |
| | PEC3 I have the resources necessary to use the system. |
| | PEC4 Given the resources, opportunities and knowledge it takes to use the system, it would be easy for me to use the system. |
| Computer Playfulness (CPLAY) | PEC4 The system is not compatible with other systems I use. |
| | CPLAY1 The following questions ask you how you would characterize yourself when you use computers: |
| | CPLAY2 . . . spontaneous |
| | CPLAY3 . . . creative |
| Computer Anxiety (CANX) | CPLAY4 . . . playful |
| | CANX1 . . . unoriginal |
| | CANX2 Computers do not scare me at all. |
| | CANX3 Working with a computer makes me nervous. |
| Perceived Enjoyment (ENJ) | CANX4 Computers make me feel uncomfortable. |
| | ENJ1 Computers make me feel uneasy. |
| | ENJ2 I find using the system to be enjoyable. |
| | ENJ3 The actual process of using the system is pleasant. |
| Objective Usability (OU) | I have fun using the system. |
| Subjective Norm (SN) | OU No specific items were used. It was measured as a ratio of time spent by the subject to the time spent by an expert on the same set of tasks. |
| | SN1 People who influence my behavior think that I should use the system. |
| | SN2 People who are important to me think that I should use the system. |
| | SN3 The senior management of this business has been helpful in the use of the system. |
| Voluntariness (VOL) | SN4 In general, the organization has supported the use of the system. |
| | VOL1 My use of the system is voluntary. |
| | VOL2 My supervisor does not require me to use the system. |
| Image (IMG) | VOL3 Although it might be helpful, using the system is certainly not compulsory in my job. |
| | IMG1 People in my organization who use the system have more prestige than those who do not. |
| | IMG2 People in my organization who use the system have a high profile. |
| Job Relevance (REL) | IMG3 Having the system is a status symbol in my organization. |
| | REL1 In my job, usage of the system is important. |
| | REL2 In my job, usage of the system is relevant. |
| Output Quality (OUT) | REL3 The use of the system is pertinent to my various job-related tasks. |
| | OUT1 The quality of the output I get from the system is high. |
| | OUT2 I have no problem with the quality of the system's output. |
| Result Demonstrability (RES) | OUT3 I rate the results from the system to be excellent. |
| | RES1 I have no difficulty telling others about the results of using the system. |
| | RES2 I believe I could communicate to others the consequences of using the system. |
| | RES3 The results of using the system are apparent to me. |
| Behavioral Intention (BI) | RES4 I would have difficulty explaining why using the system may or may not be beneficial. |
| | BI1 Assuming I had access to the system, I intend to use it. |
| | BI2 Given that I had access to the system, I predict that I would use it. |
| Use (USE) | BI3 I plan to use the system in the next <n> months. |
| | USE1 On average, how much time do you spend on the system each day? |

^aAll items were measured on a 7-point Likert scale (where 1: *strongly disagree*; 2: *moderately disagree*; 3: *somewhat disagree*; 4: *neutral* (neither disagree nor agree); 5: *somewhat agree*; 6: *moderately agree*; and 7: *strongly agree*), except computer self-efficacy, which was measured using a 10-point Guttman scale.

Avez- vous déjà utilisé la 4D ?

Veillez sélectionner une seule des propositions suivantes :

- Oui
 Non

Donnez votre avis pour évaluer l'intérêt des usages de la 4D identifiés *

Choisissez la réponse appropriée pour chaque élément :

| | Inutile | Peu utile | Neutre | Un peu utile | Utile |
|---|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1) Planification de travaux Planifier un chantier de construction en simulant les différentes phases du projet au fil du temps. Cela permet une visualisation animée du séquençage des tâches. | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 2) Suivi de chantier Suivre l'avancement d'un chantier avec la 4D. Cela permet de comparer l'avancement réel à l'avancement programmé et d'en déduire les ajustements nécessaires | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 3) Gestion du Plan d'Installation de Chantier (PIC) Gérer le PIC d'un projet de construction en simulant les différentes zones occupées au fil du temps. Cela permet une visualisation dynamique du PIC et une planification les zones d'occupation lors des différentes phases. | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 4) Gestion de la sécurité Gérer la sécurité d'un projet de construction en modélisant les équipements de sécurité nécessaires au fil du temps. Cela permet aussi de détecter les besoins en équipement de sécurité. | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 5) Détection de conflits spatio-temporels Détecter des conflits spatio-temporels (ex : interfaces entre corps de métiers) au cours du déroulement d'un chantier. | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |
| 6) Définition de la méthode de construction Définir la méthode de construction. Cela permettrait de visualiser différentes alternatives de construction afin de choisir la plus optimisée. | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> | <input type="radio"/> |

Figure 145 4D BIM uses perception exploratory

Endnotes

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- 1 <https://www.4dcollab-project.eu/>
 - 2 <https://anr.fr/Projet-ANR-16-CE10-0006>
 - 3 <https://www.fnr.lu/projects/usage-and-interaction-of-synchronous-4d-simulation-for-collaborative-decision-support-in-architecture-engineering-and-construction/>
 - 4 Original French : “UMR 3495 MAP-CRAI : L’unité mixte de recherche 3495 Modèles et simulations pour l’architecture et le patrimoine - Centre de Recherche en Architecture et Ingénierie”
 - 5 Original French : École Nationale Supérieure d'Architecture de Nancy
 - 6 Fr. niveaux de développement
 - 7 <http://www.digitalbuilding.lu/guide-application-bim>
 - 8 French original : Plan Transition Numérique dans le Bâtiment
 - 9 <https://www.tridify.com/>
 - 10 Assistant for a quality check during construction execution process for energy efficient building <https://www.accept-project.com/project.htm>
 - 11 <https://support.microsoft.com/en-us/office/show-the-critical-path-of-your-project-in-project-ad6e3b08-7748-4231-afc4-a2046207fd86>
 - 12 <https://www.oracle.com/uk/industries/construction-engineering/primavera-p6/>
 - 13 <https://www.autodesk.com/products/navisworks/features>
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 - 15 <https://visilean.com/features/>
 - 16 <https://vicooffice.dk/en/solutions/4d-scheduling-and-resource-management/>
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 - 18 <https://astapowerproject.net/products/asta-powerproject-bim/>
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 - 23 <https://www.procore.com/>
 - 24 <https://www.autodesk.fr/products/bim-collaborate/features>
 - 25 <https://www.oracle.com/industries/construction-engineering/aconex/>
 - 26 <https://www.sablono.com/product/plan?hsLang=en>
 - 27 <https://www.procore.com/bim>
 - 28 <https://redteam.com/fieldlens-the-solution/>
 - 29 Autodesk ANZ "Navisworks Manage time liner overview" <https://www.youtube.com/watch?v=wl75KuoXHwc> (accessed 01/10/2017)
 - 30 SYNCHRO Construction "SYNCHRO Pro 2017 – New Features" <https://www.youtube.com/watch?v=hnGO8oJttjs> (accessed 01/10/2017)
 - 31 Lean 4D with VisiLean <https://visilean.com/lean-4d-with-visilean/> (accessed 04/10/2019)
 - 32 <https://www.rib-software.com/en/solutions/5d-modeling>
 - 33 https://help.autodesk.com/view/ASSEMBLEPRODUCTS/ENU/?guid=About_Assemble
 - 34 <https://cubicost.com/about-us/>
 - 35 https://www.innovaya.com/prod_ov.htm
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 - 37 <https://docs.bentley.com/LiveContent/web/Bentley%20Navigator%20Desktop%20CONNECT%20Edition-v6/en/GUID-FA138A7E-067C-4563-B70B-CA4EE76A7518.html>
 - 38 RIB Software “iTWO 5D Construction method Demo1” <https://www.youtube.com/watch?v=vMHdqPntx9g> (accessed 04/10/2019)
 - 39 <https://www.veilsun.com/veilsun-qlean-construction-pull-planning>

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45 <https://www.shariing.com/>

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47 Original French Défis du Bois (<http://www.defisbois.fr/>)

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51 Original French Défis du Bois (<http://www.defisbois.fr/>)

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54 <https://www.shariing.com/en/>

55 <https://www.immersion.fr/en/>

56 Shariing specifications and functionalities <https://www.shariing.com/data/documentation/Shariing%20specifications.pdf>

57 <https://www.4dcollab-project.eu/>

58 An information system can be defined technically as a set of interrelated components that collect (or retrieve), process, store, and distribute information to support decision-making and control in an organization. In addition to supporting decision-making, coordination, and control, information systems may also help managers and workers analyze problems, visualize complex subjects.”(Laudon and Laudon, 2003)

59 As an environment for software execution and for related hardware.

60 As an end-user software designed for specific tasks.

61 <https://forge.autodesk.com/developer/documentation>

62 <https://www.figma.com/about/>

63 <https://git-scm.com/>

64 <https://github.com/>

65 <https://webpack.js.org/concepts/>

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67 <https://vuejs.org/v2/guide/>

68 <https://www.mulesoft.com/resources/api/what-is-rest-api-design>

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70 Revit BIM Features <https://www.autodesk.com/products/revit/features?plc=RVT&term=1-YEAR&support=ADVANCED&quantity=1>

71 Archicad Basic Concepts - Visualizing and Filtering Building Information
<https://helpcenter.graphisoft.com/knowledgebase/86708/>

72 Vectorworks BIM Features <https://www.vectorworks.net/en-GB/architect/features?filterBy=Capability&filterValue=Building+Information+Modelling>