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Short circuit valorization of thermoplastic waste for the conception by 3D printing of composite structures

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Valorisation en circuit court de déchets thermoplastiques pour la conception par impression 3D de structures composites

Short circuit valorization of thermoplastic waste for the conception by 3D printing of composite structures

Doctoral Dissertation

Submitted and defended publicly on December 11th 2020

in a partial fulfillment of the requirements for obtaining a:

PhD title from the University of Lorraine

(Spec: Industrial System Engineering)

By

Pavlo Javier Alejandro SANTANDER TAPIA

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en agradecimiento a su apoyo
incondicional.*

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Résumé étendu en français (Extended abstract in French)

Introduction

Aujourd'hui, notre société est confrontée à des défis importants afin de parvenir à une société ayant une meilleure gestion des ressources disponibles en quantité limitée telles que les énergies fossiles ainsi qu'à une meilleure prise en compte de l'impact des choix énergétiques sur le climat. Afin d'atteindre ces objectifs, de nombreux changements économiques, sociaux, organisationnels et technologiques doivent être mis en œuvre¹. Si l'on considère les hydrocarbures, on se rencontre que l'utilisation et l'élimination des plastiques est un problème majeur qui doit encore être résolu dans la perspective d'un développement plus durable des activités humaines. Actuellement de nombreux gouvernements tentent de réduire son usage mais paradoxalement la consommation à usage d'emballages n'a jamais été aussi forte qu'aujourd'hui avec près de 250 millions de tonnes de déchets produits dans le monde. Bien qu'une quantité importante de matière plastique utilisée puisse être potentiellement recyclée, si nous considérons le plastique généré depuis 1950, seul 9% a été recyclé à l'échelle de la planète [1] et, si on considère l'Europe (qui est supposée être la région la plus avancée en matière de programmes de recyclage), seulement 14% du plastique produit a été recyclé en 2016² [2], [3]. Partant de ce constat, la recherche doit pouvoir offrir de nouvelles options de valorisation afin d'augmenter le taux de recyclage du plastique et de contribuer aux défis socio-environnementaux autour de ce matériau.

Depuis une dizaine d'année on assiste à l'émergence de la technologie d'impression 3D. Parmi les différents procédés celui dit de dépôt par filament fondu est le plus répandu du fait d'un coût très faible d'équipement et du développement en open source de ces machines. Cette technologie permet une fabrication décentralisée d'objets à partir de thermoplastique. Partant de ce constat différents auteurs ont vérifiés la possibilité de réutiliser des matières plastiques usagées par ces machines [4]. Au vu des résultats encourageant, le recyclage distribué du plastique à l'aide de technologies 3D open source (imprimantes 3D et extrudeuses) est apparu dans la communauté scientifique comme une option possible pour la valorisation des déchets plastiques. D'une part, la notion d'open source (OS) permet de créer des équipements techniquement supérieurs et bien moins chers que les modèles propriétaires [5], [6]. D'autre part, le recyclage distribué des plastiques peut être imaginé comme une sorte de "réseau intelligent", composé de petites unités de recyclage coordonnées qui fournissent du filament recyclé à la communauté de l'impression 3D. Contrairement au paradigme actuel du recyclage centralisé, cette nouvelle approche du recyclage propose un recyclage local en petites quantités. Sous ce nouveau paradigme, les problèmes économiques et environnementaux du recyclage centralisé seraient potentiellement évités, principalement en raison de l'utilisation d'une technologie OS moins coûteuse, de courtes distances de récupération et du transport en faible

¹ CORDIS, "SOCIAL CHALLENGES - Climate action, Environment, Resource Efficiency and Raw Materials," 2014. [Online]. Available: <https://cordis.europa.eu/programme/id/H2020-EU.3.5>. [Accessed: 21-Aug-2020]

² PlasticsEurope, "Plastics-the facts 2017, An analysis of European plastics production, demand and waste data," 2017.

quantité des déchets plastiques. La revue de la littérature réalisée par [Cruz Sanchez et al. \[4\]](#) sur le recyclage distribué du plastique pour l'impression 3D a montré que la plupart des études existantes se sont concentrées sur les étapes dites de compoundage (compounding), de réalisation de la matière première (feedstock) et d'impression (printing) (voir [Figure 1](#)), tandis que les étapes de récupération (recovery) et de préparation (preparation) ont été moins étudiées. A partir de cette revue nous pouvons conclure que la revalorisation par l'impression 3D des thermoplastiques est possible d'un point de vue technique (étapes III, IV, V et VI de la [Figure 1](#)). Cependant, sa faisabilité du point de vue de la logistique/chaîne d'approvisionnement (étape I [Figure 1](#)) doit encore être démontrée, correspondant à l'objectif de cette recherche. Pour démontrer la faisabilité de la mise en œuvre de ce type de recyclage, la condition de durabilité est aujourd'hui requise. Du point de vue de l'évaluation de la durabilité, un système est durable s'il intègre les dimensions économique, environnementale et sociale, traditionnellement appelées les trois piliers de la durabilité ("triple bottom-lines - TBL") [7]. En outre, [Bautista et al. \[8\]](#) propose l'intégration des dimensions politiques et technologiques (TBL+) si elles ont une grande importance dans le système évalué. Compte tenu du grand nombre d'éléments à prendre en compte, qui rendent le système très complexe pendant le processus d'évaluation, des méthodes et des outils d'évaluation sont nécessaires dès les premières étapes du projet afin d'analyser ses impacts et définir les conditions de son déploiement. Compte tenu de cette problématique, nous allons au cours de cette thèse chercher à apporter des réponses à la question de recherche suivante : **Dans quelles conditions est-il possible de déployer un réseau durable de recyclage local et distribué des plastiques en utilisant des technologies d'impression 3D open source ?** Considérant ce qui précède, ce travail de recherche vise à proposer un cadre pour l'analyse et l'évaluation, du point de vue de la durabilité, de l'approche de recyclage distribué du plastique pour l'impression 3D. Grâce à la modélisation de systèmes complexes nous proposerons un processus décisionnel favorisant l'émergence de chaînes d'approvisionnement durables en matière de recyclage.

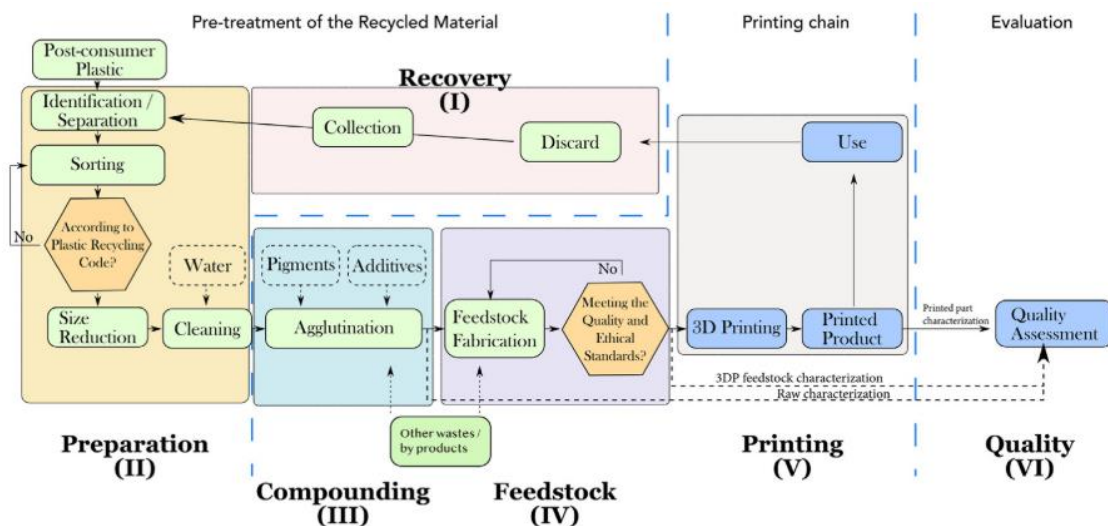


Figure 1. Étapes du recyclage distribué des plastiques pour l'impression 3D (Source : [Cruz Sanchez et al. \[4\]](#)).

Dans un premier temps, au moyen d'une revue de la littérature, nous allons chercher à comprendre selon quels critères les réseaux de recyclages de plastiques sont définis et évalués.

État de l'art

Dans le premier chapitre, une revue de la littérature a été réalisée afin d'explorer les paradigmes de recyclage du plastique étudiés dans la littérature, ainsi que leurs méthodologies et critères d'évaluation. Les résultats de cette revue de la littérature correspondent à la première contribution de cette thèse. Suite à l'analyse de 57 documents issus des plus grandes bases d'articles (Scopus, Springer et Web of Science) nous pouvons conclure que dans le contexte du recyclage du plastique, le paradigme du recyclage distribué n'a pas encore été abordé du point de vue du réseau. Par conséquent, ce travail correspond à la première contribution à ce paradigme qui, selon le contexte de la littérature, pourrait être réalisé en utilisant la technologie d'impression 3D. Du point de vue de l'évaluation, les résultats ont montré que les réseaux de recyclage des plastiques ont été évalués principalement en tenant compte des aspects économiques et environnementaux, alors que les aspects sociaux, technologiques et politiques de la durabilité ont été rarement pris en compte. Enfin, en tant qu'outils d'évaluation, les résultats ont montré que l'approche d'optimisation a été la plus considérée.

Sur la base des résultats obtenus dans le premier chapitre, nous avons exploré dans le deuxième chapitre comment les aspects sociaux, technologiques et politiques devraient être pris en compte pour une évaluation plus holistique des réseaux de recyclage du point de vue de la durabilité. Comme résultat de la revue de 129 documents, un ensemble de critères et d'indicateurs pour les dimensions sociales, technologiques et politiques ont été extraits pour cette évaluation et d'autres (voir [Tableau 1](#)). Ceci correspond à la deuxième contribution de cette thèse.

Tableau 1. Proposition d'intégration de la dimension sociale, technologique et politique

Dimension	Principaux critères	Critères suggérés (en complément des principaux)
Social	Création d'emplois Santé et sécurité des travailleurs Santé et sécurité des consommateurs Développement local Coût social du carbone Donation à la communauté Image de l'entreprise Satisfaction des consommateurs	Inclusion sociale
Technologique	Capacité des installations Capacité des véhicules Taux de recyclage Sélection de la technologie et de la récupération	Qualité du produit recyclé Qualité du produit retourné Taux de conversion
Politique	Subventions à l'investissement ou par produit recyclé Politiques d'émissions (quota et limite) Limites légales (collecte, recyclage, etc.) Pénalités et taxes	

Proposition méthodologique

Dans le troisième chapitre, une analyse des méthodologies, les plus représentatives permettant la modélisation des systèmes complexes, a été réalisée. L'étude des avantages et des inconvénients de chacune d'entre elles, ainsi que l'adaptabilité au problème de la conception du circuit court du recyclage nous a permis, afin de sélectionner la méthodologie la plus appropriée. À partir des analyses de littérature réalisées dans les chapitres précédents, il a été conclu que l'optimisation, les systèmes dynamiques, la théorie des jeux et les méthodes multicritères correspondent aux méthodologies les plus utilisées pour l'évaluation des réseaux de recyclage. La sélection a été réalisée en prenant en compte les critères suivants : (1) Intégration d'objectif multiples incluant les dimensions de durabilité (2) l'Intégration des aspects quantitatifs et qualitatifs simultanément, (2) les considérations de temporalité des paramètres du modèle et, (4) la prise en compte de décisions des opérations logistiques. Comme résultat du processus de sélection, un cadre conceptuel à deux niveaux a été proposé pouvant être utilisé dans cette évaluation et dans d'autres évaluations des approches de recyclage distribué. Ainsi, le système étudié dans cette recherche peut être évalué du point de vue de la durabilité, en considérant en même temps les complexités opérationnelles et des variables exogènes qui y sont présentes. Ce cadre d'évaluation, correspond à la troisième contribution de cette thèse. Plus précisément, l'approche de modélisation (voir Figure 2), elle propose une analyse du point de vue du système (couche supérieure) et du point de vue opérationnel (couche inférieure). La dynamique des systèmes et l'optimisation mathématique ont été proposées comme méthodologies pour la couche supérieure et la couche inférieure respectivement. La dynamique des systèmes a été proposée afin de prendre en compte les aspects exogènes et qualitatifs qu'il n'est pas possible de considérer au moyen de modèles d'optimisation traditionnels.

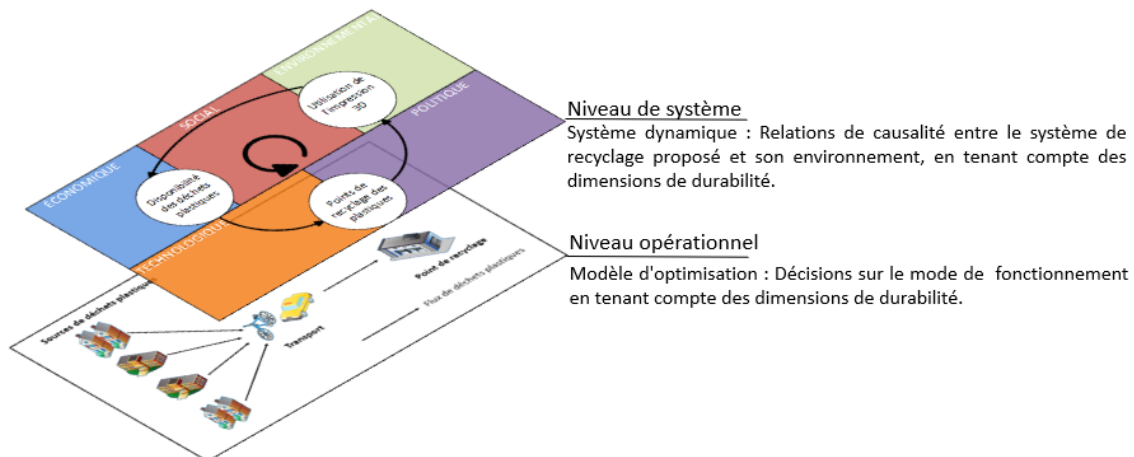


Figure 2. Approche de modélisation à deux couches pour le recyclage distribué du plastique en utilisant des technologies 3D open source

Développement et application des modèles au cas d'étude

Dans le quatrième chapitre, le modèle d'optimisation proposé pour l'évaluation du recyclage distribué des plastiques du point de vue logistique a été présenté. Ce modèle correspond à la quatrième contribution de cette thèse. Il s'agit à notre connaissance de la première formalisation, du point de vue logistique, du recyclage distribué du plastique en utilisant la technologie d'impression 3D. Le modèle développé permet aux décideurs de sélectionner les sources de déchets à partir desquelles les déchets polymères doivent être collectés, le nombre de routes de collecte nécessaires, la séquence des routes de collecte et les moyens de transport à utiliser sur chaque route. Le modèle se base sur une maximisation des bénéfices économiques et environnementaux tout au long de l'opération de recyclage. Plus précisément, le modèle développé correspond à un modèle MILP (Mixed-integer linear programming en anglais) mono-objectif, qui maximise la rentabilité économique (la partie environnementale est réduite à une grandeur extensive à savoir le coût d'émission de CO₂). Bien que reducteur sur la notion de durabilité, le modèle permet de calculer les bénéfices (économique et en émissions de CO₂ équivalent) de la future activité en comparant le coût obtenu par les deux réseaux d'approvisionnement proposés, avec et sans recyclage distribué dans un objectif de conception du système (voir Figure 3).

D'une part, le bénéfice économique correspond à la quantité d'argent économisée grâce au recyclage d'une quantité de déchets plastiques qui est transformée en filament pour l'impression 3D. Il est calculé comme étant la différence entre les coûts du filament recyclé et du filament vierge. Le coût d'acquisition comprend le prix d'achat du filament sur le marché et le coût de livraison. Le coût de recyclage correspond au coût d'obtention du filament en recyclant la quantité de déchets plastiques, qui prend en compte le coût de la main d'œuvre et du transport pour la collecte des déchets plastiques ainsi que le coût de la main d'œuvre et du traitement (recyclage) des déchets plastiques comme représenté dans la figure 3. D'autre part, selon notre définition préalable, afin de développer un premier modèle, le bénéfice environnemental correspond à la quantité d'émissions de dioxyde de carbone équivalent évitée grâce au recyclage d'une quantité de plastique, exprimée en unités monétaires [9], [10]. Plus précisément, il correspond à la différence entre la quantité d'émissions résultant 1) du processus de fabrication et du transport d'une quantité de filament plastique 3D commercial, et 2) la quantité d'émissions résultant du recyclage local (collecte et fabrication) de la même quantité de matière pour obtenir le filament plastique 3D. Le tout en termes monétaires.

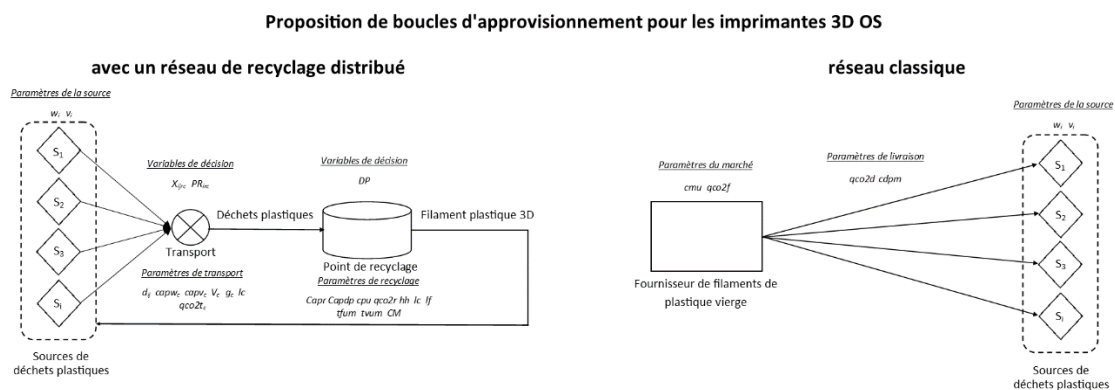


Figure 3. Modèle conceptuel du réseau de recyclage

Les restrictions utilisées dans ce modèle sont liées aux caractéristiques ou conditions associées à (1) la route de collecte, (2) le moyen de transport utilisé, (3) la capacité de traitement, et (4) la non-négativité des variables.

Le modèle d'optimisation développé a été appliqué en considérant comme étude de cas la ville de Nancy située dans la région de Lorraine, en France. La région Lorraine dispose d'un programme de soutien à l'intégration et à la diffusion des technologies d'impression 3D dans les écoles secondaires. Pour atteindre cet objectif, un programme d'investissement a été établi afin de fournir à chaque école secondaire des imprimantes 3D dans le cadre du programme scolaire³. Depuis 2014, le Lorraine Fab Living Lab (LF2L), la plateforme d'innovation du laboratoire ERPI, dans le cadre d'un projet pluridisciplinaire "le GreenFabLab⁴", envisage la mise en place d'une filière locale de recyclage de plastique pour fournir du filament recyclé aux écoles et lycées de Nancy.

Les résultats de la solution obtenue (voir [Tableau 2](#)) ont montré qu'un bénéfice total de 46,25 € par mois a été obtenu, ce qui correspond à la somme du bénéfice économique et du bénéfice environnemental mensuels, avec des valeurs de 45,39 € par mois et de 0,86 € par mois respectivement. La quantité totale de déchets plastiques PLA à collecter est de 8,30 kg par mois. Ce plastique est collecté sur une distance totale de 25,52 km. Toute cette opération nous permet de ne plus émettre 43,12 kg de CO₂ eq., ce qui correspond à une réduction de 86,12 % du CO₂ eq. par rapport à la situation actuelle. La solution modèle dérivée montre un certain nombre de 1 chemin fermé nécessaire pour collecter les déchets de plastique PLA de 23 écoles/lycées sélectionnées sur 23 écoles/lycées potentielles. Pour effectuer la collecte, la solution modèle a proposé le parcours indiqué dans la [figure 4](#). Une seule voiture est nécessaire pour effectuer la collecte en suivant la route indiquée dans la [figure 4](#).

Tableau 2. Résultats

Index	Valeur
Bénéfice total (€)	46.25
Bénéfice économique (€)	45.39
Coût alternatif total (€)	149.40
Coût total de la livraison du filament plastique (€)	Non considéré
Coût total du transport (€)	3.98
Coût total de la main-d'œuvre dans le transport (€)	21.47
Coût total du traitement (€)	7.31
Coût total de la main-d'œuvre pour le traitement (€)	28.31
Coût d'amortissement de la machine (€)	42.95
Bénéfice environnemental (€)	0.86
Coût total des émissions par fabrication (€)	0.30
Coût total des émissions par livraison de filament plastique (€)	0.70
Coût total des émissions par le recyclage (€)	0.09
Coût total des émissions par le transport (€)	0.05
Quantité collectée (kg)	8.30
Quantité disponible (kg)	8.30
Nombre de points disponibles pour la collecte	23
Nombre de points collectés	23
Jours de traitement	5
Nombre de routes	1
Distance totale parcourue (km)	26.52
Distance totale en moto (km)	0

³ F. Robine and R. Tomasini, "Le 'FabLab', un incubateur de créativité et d'innovation. La lettre de la pédagogie 6.," 2018.

⁴ <http://lf2l.fr/projects/green-fablab/>

Tableau 3. Résultats (continuation)

Index	Valeur
CO ₂ eq. non émis (kg)	43.12
Écart relatif	0.04
Écart absolu	2.05
Meilleur possible	48.30
Utilisation des ressources (secondes)	7200



Figure 4. Carte de solution

Afin d'évaluer comment le résultat change par rapport aux paramètres du modèle, une analyse de sensibilité a été effectuée avec un ensemble de paramètres sélectionnés. Ce type d'analyse permet d'analyser les résultats dans différents scénarios. Dans cette recherche, l'influence sur le bénéfice total (économique et environnemental) des paramètres suivants a été analysée : quantité de déchets plastiques par imprimante et coût d'achat des filaments plastiques. L'analyse de sensibilité réalisée à partir de l'étude de cas nous a permis de définir les conditions minimales requises, en fonction de l'évolution possible du marché (en termes de quantité de déchets plastiques PLA et de prix des filaments vierges) dans lequel le réseau local de recyclage des plastiques en petites quantités est faisable. Par exemple, à partir de l'analyse de sensibilité, il a été observé que si la quantité de déchet plastique obtenu par mois par imprimante change, on peut obtenir un bénéfice et ce jusqu'à un prix de filament vierge plancher de 6.29 euros par kilogramme (voir [Figure 5](#)).

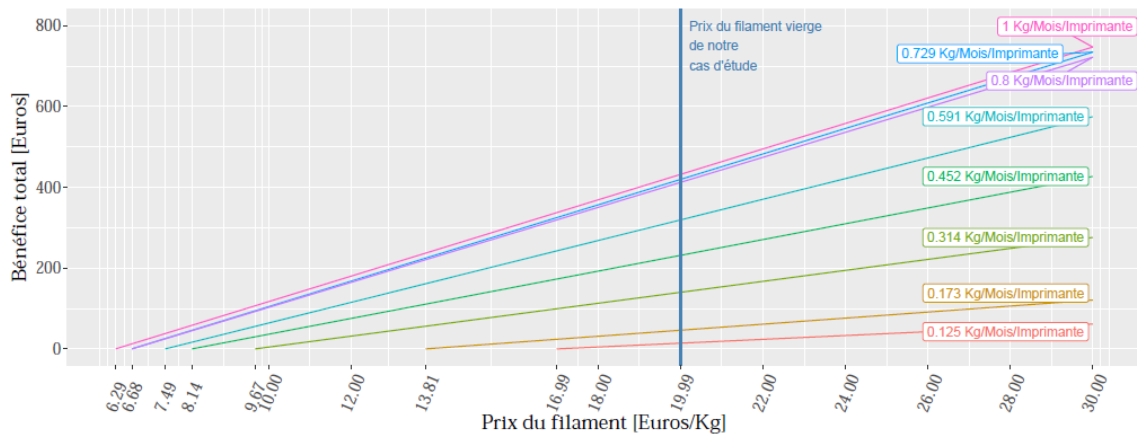


Figure 5. Analyse de sensibilité du modèle avec variation du prix des filaments plastiques

En conclusion, ce chapitre a permis de montrer les bénéfices économiques et environnementales (en termes de CO₂ eq. évité), d'un point de vue logistique, du recyclage distribué des plastiques pour l'impression 3D. Les résultats obtenus de l'application du modèle à l'étude de cas et de son analyse de sensibilité suggèrent la reproduction de ce nœud de recyclage en différents endroits pour former le réseau de recyclage distribué. Cependant, comme le montre l'analyse de sensibilité, le système dépend d'autres éléments déterminés par le contexte, tels que la demande d'imprimantes 3D et la consommation de filament. Pour cette raison, un modèle basé sur la dynamique de systèmes a été développé dans le chapitre suivant afin d'intégrer ces éléments et d'autres dans l'évaluation.

Le cinquième chapitre présente le modèle de dynamique de système développé pour l'évaluation, du point de vue de la durabilité, du recyclage distribué du plastique à l'aide de l'impression 3D. Le modèle développé correspond à la cinquième contribution de cette thèse, formalisant cette approche de recyclage du point de vue du système. Le modèle de système dynamique a été développé à partir de la construction de 5 sous-systèmes identifiés dans le contexte du recyclage distribué des plastiques (voir figure 6). Ces sous-systèmes correspondent à : (1) marché de l'impression 3D, (2) marché des filaments 3D en plastique recyclé, (3) mise en place de petits centres de recyclage du plastique, (4) génération de déchets et (5) capacité de la chaîne de recyclage.

- **Marché de l'impression 3D** : Dans ce sous-système, le comportement de la demande d'imprimantes 3D est modélisé. Ce sous-système détermine le potentiel du système distribué, puisqu'il détermine le nombre d'imprimantes 3D à fournir.
- **Marché du filaments 3D en plastique recyclé** : Dans ce sous-système, l'interaction entre la demande de filament plastique recyclé et l'offre de filament plastique recyclé est modélisée. D'une part, la demande de filament plastique recyclé dépend du développement de l'impression 3D (sous-système du marché de l'impression 3D). D'autre part, l'offre de filament plastique recyclé, dans le contexte du recyclage distribué du plastique, dépend du nombre de points de recyclage disponibles dans chaque période (sous-système pour la mise en place de petits centres de recyclage des plastiques).

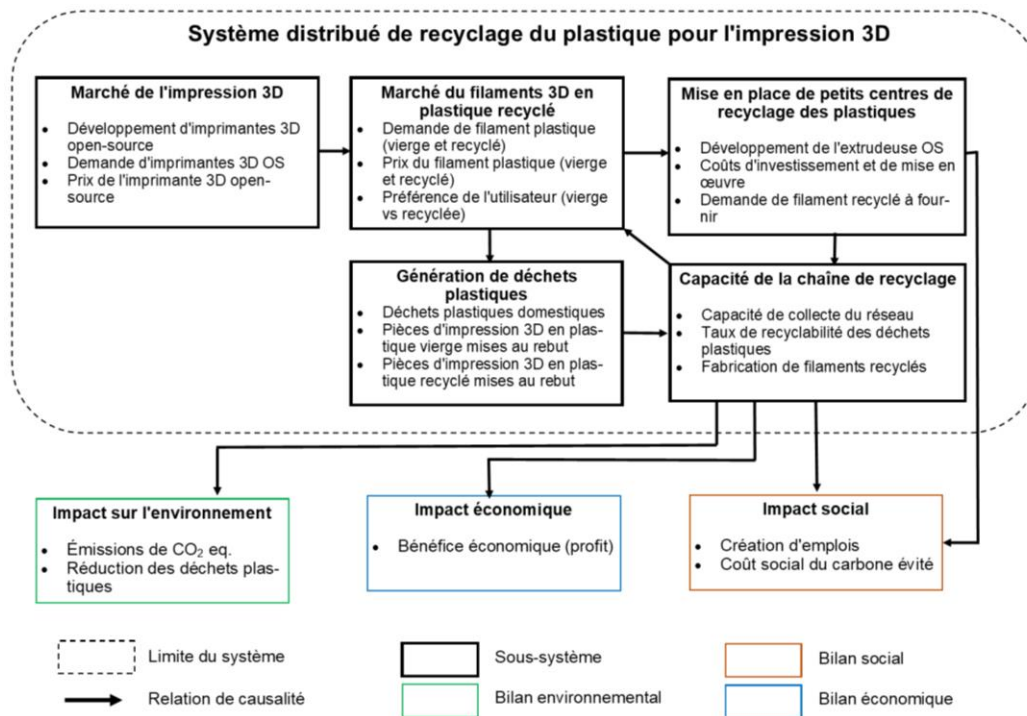


Figure 6. Structure du système distribué de recyclage des plastiques

- Mise en place de petits centres de recyclage des plastiques** : Dans ce sous-système, la motivation de la mise en place de petits centres de recyclage est modélisée, c'est-à-dire les facteurs qui influencent la décision de mise en place d'installations de recyclage des plastiques. Comme facteurs, nous faisons référence à des éléments tels que, l'investissement nécessaire (l'achat d'une extrudeuse et d'autres équipements) et la demande de filaments recyclés à fournir (sous-système du marché des filaments 3D en plastique recyclé).
- Génération de déchets** : La génération de déchets plastiques est un aspect important qui doit être pris en compte, car il correspond à la matière première à traiter. Dans ce sous-système, trois types de sources de déchets plastiques peuvent être identifiés : (1) les déchets plastiques domestiques, (2) les pièces d'impression 3D mises au rebut et fabriquées à partir de filaments vierges et (3) les pièces d'impression 3D mises au rebut et fabriquées à partir de filaments recyclés. En même temps, la quantité de déchets plastiques produits dépend des taux de déchets de ces sources.
- Capacité de la chaîne de recyclage** : Dans ce sous-système, la capacité de collecte et de recyclage du réseau est modélisée, qui dépend du nombre de points de recyclage disponibles et de la capacité de la chaîne de recyclage (l'ensemble des machines). Dans ce sous-système, la recyclabilité des déchets plastiques collectés (qui dépend de la qualité ou du niveau de dégradation des déchets plastiques) doit être prise en compte.
- Paramètres de sorties** : Sachant qu'un plus grand nombre de critères sont nécessaires pour considérer tous les défis de l'industrie de la transformation des plastiques, partiellement les critères suivants sont proposés comme critères d'évaluation du système de recyclage des plastiques distribués du point de vue de la durabilité. En tant

que critères économiques, le bénéfice économique (profit) du réseau est pris en compte. En tant que critères environnementaux, les émissions de CO₂ équivalents et la quantité de déchets plastiques recyclés sont mesurées. Enfin, en tant que critères sociaux, la création d'emplois et le coût social du carbone évité sont pris en compte. Les dimensions technologiques et politiques sont prises en compte à travers des éléments du modèle.

Dans le contexte du recyclage distribué du plastique pour l'impression 3D, il est possible d'identifier deux types d'utilisateurs et deux types de fournisseurs de filaments de plastique recyclé. En ce qui concerne les utilisateurs de l'impression 3D, il est possible d'identifier des utilisateurs particuliers et des utilisateurs institutionnels. Les utilisateurs particuliers sont considérés comme les personnes qui utilisent l'impression 3D à domicile. D'autre part, les utilisateurs institutionnels sont les organisations qui utilisent l'impression 3D à des fins éducatives (collèges, lycées, universités) ou à des fins commerciales. En tant que fournisseurs potentiels de filaments de plastique recyclé, nous identifions deux types de fournisseurs différents : d'une part, les institutions à but lucratif, c'est-à-dire, les institutions qui considèrent le recyclage du plastique pour l'impression 3D comme une activité commerciale (ceci est le cas de la startup Qactus⁵, au Chili) et d'autre part, les institutions à but non lucratif, c'est-à-dire, qui ne considèrent pas le recyclage du plastique comme une activité commerciale (des associations, ou bien des laboratoires universitaires). Ces deux types d'acteurs ont été pris en considération, en intégrant leurs objectifs particuliers. Du côté des utilisateurs de l'impression 3D, les établissements d'enseignement tels que les lycées, les collèges et les universités ont été pris en compte. D'autre part, en tant que fournisseurs de filaments plastiques recyclés, seules les institutions à but non lucratif ont été prises en compte. Finalement, comme unité fonctionnelle du système, un kilogramme de filament plastique (vierge ou recyclé) utilisable en impression 3D a été considéré.

Dans la modélisation des systèmes dynamiques, la première étape est la création d'un diagramme de causalité [11]–[13]. Le but principal d'un diagramme de causalité est (1) d'identifier la variable principale du système en fonction du problème spécifié, et (2) de montrer les relations entre les éléments considérés dans le système. La Figure 7 représente le diagramme de boucle causale obtenu intégrant chaque sous-système expliqué précédemment. L'un des principaux aspects à souligner du système est l'apparition de douze boucles d'équilibrage contre trois boucles de renforcement. Une boucle de renforcement correspond aux cycles causaux dans lesquels une modification d'une variable cause un retour positif dans la même variable (à cause de son interaction avec les autres éléments du système) [13]. D'autre part, une boucle d'équilibrage correspond aux cycles causaux dans lesquels une modification d'une variable provoque un retour négatif (contrôle) dans la même variable [13]. Cet aspect structurel des systèmes est basé, d'une part, sur des boucles de contrôle de flux de masse (déchets plastiques, déchets plastiques recyclables et filament recyclé obtenu). D'autre part, il est également possible d'observer des boucles de contrôle pour la mise en place d'installations de recyclage, qui sont contrôlées en fonction de la capacité de collecte et de fabrication des installations existantes. Enfin, la demande de chaque matériau (filament recyclé et vierge), qui dépend de la demande des imprimantes 3D et de la consommation de filament, est considérée comme une entrée du système.

⁵ <https://qactus.cl/>

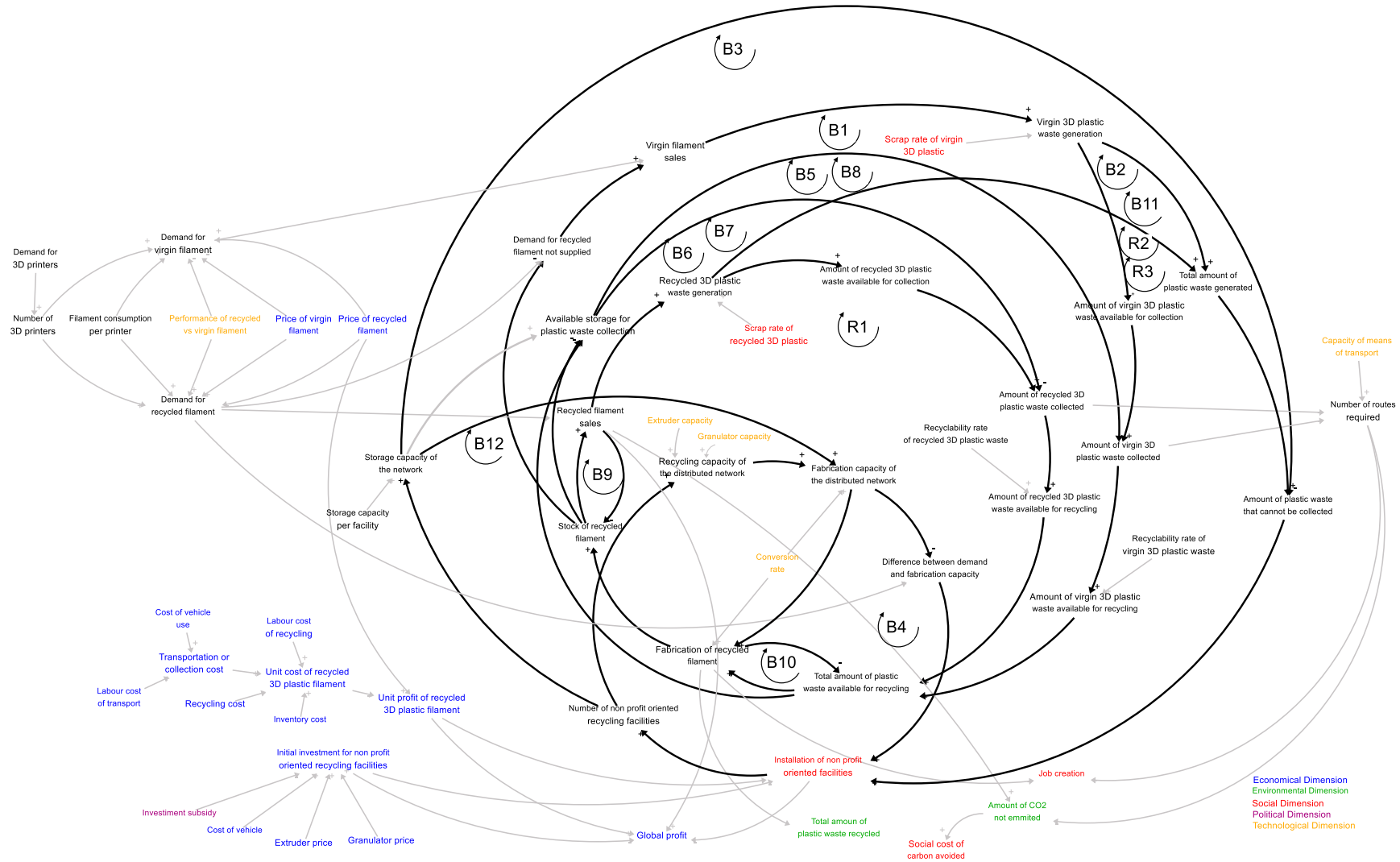


Figure 7. Diagramme de boucle causale pour le recyclage distribué des plastiques

La deuxième étape correspond à la construction du diagramme des flux et des stocks. Le diagramme des flux et des stocks représente l'accumulation (stock) des variables, qui varie en fonction de leurs flux (taux) dans le temps. La [figure 8](#) présente le diagramme des stocks et des flux obtenu pour le recyclage distribué des plastiques (voir le chapitre 5 pour les équations).

Tout comme au chapitre précédent, le modèle a été appliqué au cas du Lorraine Fab Living Lab (LFL2) pour le recyclage des déchets plastiques PLA d'impression 3D des collèges et lycées de Nancy, France. Considérant ce qui précède, le scénario de base suivant a été étudié :

- **Scénario de base** : Le LF2L a déjà investi dans les machines nécessaires pour réaliser le processus de collecte et de recyclage des plastiques (extrudeuse, broyeur et moyens de transport). Comme sources de déchets, seuls les déchets plastiques PLA provenant de l'impression 3D sont pris en compte. Ces déchets plastiques seront collectés auprès des mêmes collèges et lycées qui seront approvisionnés.

Le [Tableau 3](#) présente les résultats obtenus pour chaque indicateur en considérant une période d'étude de 10 ans avec un pas de temps mensuel. Le profit global a été calculé en tenant compte de l'investissement réalisé et des revenus générés par la vente de filaments recyclés. La quantité de déchets plastiques recyclés a été calculée en tenant compte de la quantité de filaments recyclés fabriqués. La quantité de CO₂ eq. non émise a été calculée en comparant les émissions dues à la collecte des déchets plastiques et à la fabrication de filaments recyclés, par rapport aux émissions dues à l'utilisation de filaments vierges. Le coût social évité a été calculé en fonction de la quantité de CO₂ eq. non émise. La création d'emplois a été considérée en fonction des heures de travail pour la collecte et le recyclage des déchets plastiques, et enfin le nombre d'installations de recyclage nécessaires est calculé en fonction de la demande de filament recyclé, de la disponibilité des déchets et de la rentabilité éventuelle obtenue.

Tableau 4. Résultats

Année	Profit global (euros)	Quantité totale de déchets plastiques recyclés (Kg de déchets plastiques)	CO ₂ eq. non émis (économisé) (Kg de CO ₂ eq.)	Coût social évité (euros)	Création totale d'emplois (Emplois)	Nombre d'installations de recyclage
Année 1	-2569.45	12.29	47.83	2.22	0.14	1
Année 2	-2226.55	56.58	241.15	11.21	0.24	1
Année 3	-1406.30	129.72	577.54	26.86	0.36	1
Année 4	-587.04	202.77	913.49	42.48	0.47	1
Année 5	232.21	275.82	1249.44	58.10	0.58	1
Année 6	-1443.60	356.18	1618.99	75.28	0.71	1
Année 7	-624.35	429.24	1954.94	90.90	0.82	1
Année 8	194.91	502.29	2290.89	106.53	0.94	1
Année 9	1096.09	582.65	2660.44	123.71	1.06	1
Année 10	1915.34	655.70	2996.39	139.33	1.18	1

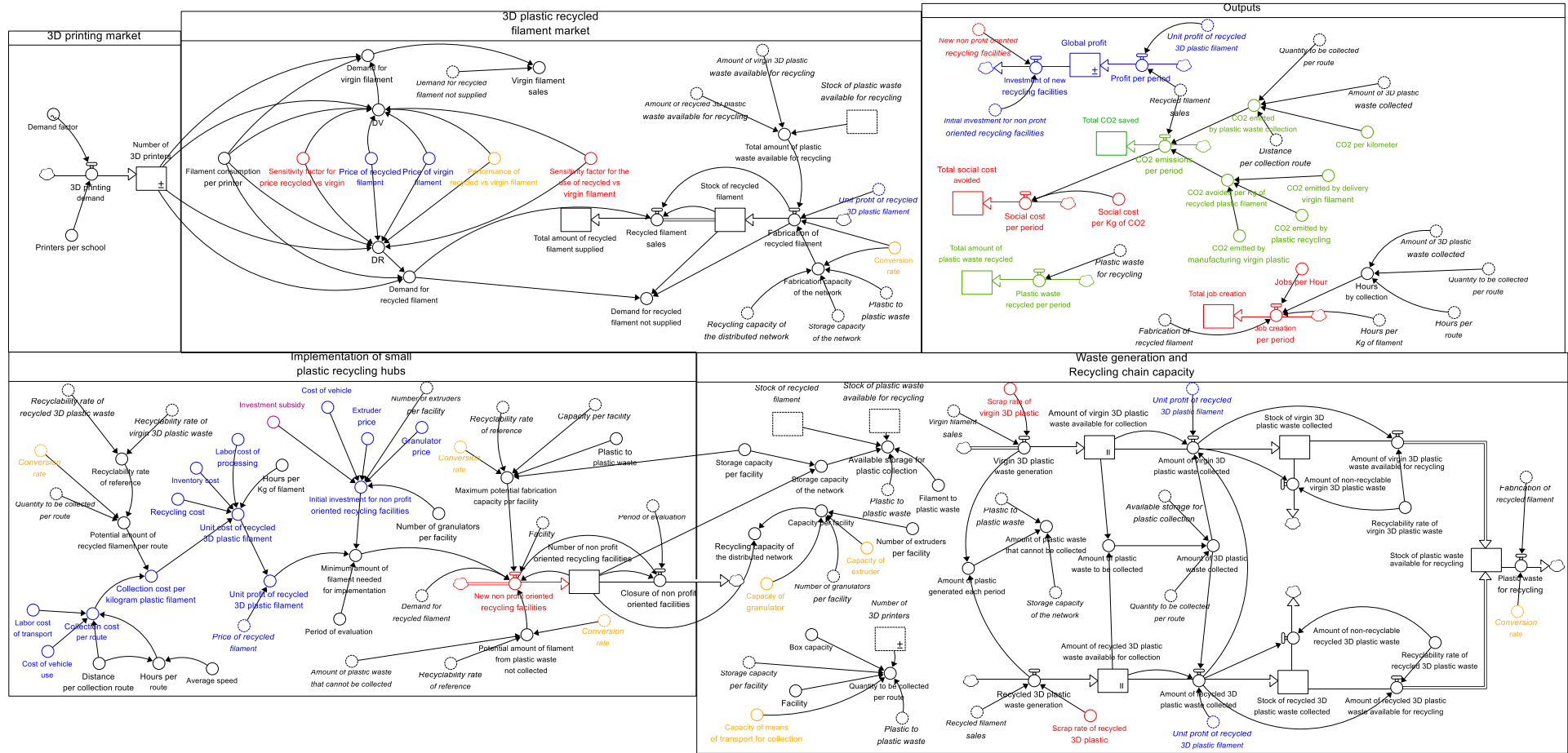


Figure 8. Diagramme des stocks et des flux pour le recyclage distribué des plastiques.
 Bleu = dimension économique, vert = dimension environnementale, rouge = dimension sociale, orange = dimension technologique, violet = dimension politique.

Les résultats obtenus ont montré, d'un point de vue économique, que l'investissement (2577 euros en considérant une extrudeuse et une broyeuse) est récupéré en moins de 5 ans. Après 5 ans, un réinvestissement pourrait être effectué, puisque les conditions imposées pour la mise en œuvre d'une nouvelle installation (condition de récupération de l'investissement, condition de capacité et condition de disponibilité des déchets) sont remplies. Compte tenu des indicateurs environnementaux, les résultats ont montré qu'un total de 655.70 kg de déchets plastiques serait recyclé par le système en 10 ans et qu'un total de 2996.39 kg de CO₂ eq. serait évité grâce au processus de recyclage. Du point de vue social, un coût social équivalent à 58.10 euros serait évité en 5 ans et 139.33 euros en 10 ans. En ce qui concerne la création d'emplois, l'équivalent à 1.18 mois d'emploi seraient créés. Finalement, une seule installation de recyclage serait nécessaire pour réaliser l'ensemble du processus.

Comme pour le chapitre précédent, une analyse de sensibilité a été réalisée afin d'analyser le comportement du système dans différents scénarios. Sept variables ont été considérées séparément : Prix du filament recyclé, Prix du filament vierge, Consommation de filament par imprimante, Subvention à l'investissement, Imprimantes par collège, Taux de mise au rebut et coût de la main-d'œuvre. Le [Tableau 4](#) présente un résumé des résultats obtenus de l'analyse de sensibilité réalisée. Chaque cellule indique le degré de sensibilité de chaque indicateur par rapport à la variation de la variable d'entrée.

Tableau 5. Résultats des analyses de sensibilité. Degré de sensibilité des indicateurs aux variations des variables d'entrée.

		Sorties					
		Quantité de déchets plastiques recyclés	Profit global	CO ₂ eq. non émis	Coût social évité	Création d'emplois	Nombre d'installations de recyclage
Variables	Prix du filament recyclé	Haut	Haut	Haut	Haut	Faible	Haut
	Prix du filament vierge	Moyen	Moyen	Moyen	Moyen	Faible	Moyen
	Consommation de filaments	Haut	Haut	Haut	Haut	Haut	Moyen
	Subvention à l'investissement	Non sensible	Haut	Non sensible	Non sensible	Non sensible	Non sensible
	Imprimeurs par établissement scolaire	Haut	Haut	Haut	Haut	Faible	Faible
	Taux de rebut	Haut	Haut	Haut	Haut	Haut	Moyen
	Coût du personnel par heure	Moyen	Haut	Moyen	Moyen	Faible	Faible

Finalement, sur la base des résultats de l'analyse de sensibilité, deux scénarios (optimiste et pessimiste) ont été proposés et analysés. L'analyse de ces scénarios a montré la forte dépendance du système par rapport à la génération de déchets plastiques et au prix du filament recyclé. En particulier, les deux scénarios montrent l'importance d'une subvention pour renforcer le développement de cette approche de recyclage. Quel que soit le scénario, une subvention diminue l'investissement et favorise la mise en place d'installations de recyclage, permettant ainsi de recycler plus de déchets plastiques. D'autre part, la forte dépendance du système vis-à-vis de la génération de déchets plastiques, rend

nécessaire la prise en compte d'autres sources de déchets d'impression 3D (pas seulement les établissements d'enseignement), ce qui pourrait accroître les bénéfices obtenus.

Conclusions et perspectives

Ces travaux de recherche ont permis d'explorer la faisabilité d'un tel système en intégrant simultanément des dimensions de durabilité (basée sur l'approche TBL+), du recyclage distribué du plastique au moyen d'un cas d'étude spécifique. Les résultats de l'application de la méthodologie proposée (basée sur optimisation et la dynamique de systèmes) ont montré leur pertinence pour la conception de réseaux locaux de recyclage de plastique. Le potentiel d'un tel réseau reside dans la diffusion actuelle et future de l'impression 3D. Les modèles développés peuvent également être utilisés pour aider à la prise de décisions en matière de logistique et de mise en place pendant l'évaluation de la durabilité de cette approche de recyclage.

Comme cette recherche est la première à aborder le recyclage distribué des plastiques du point de vue de la logistique, de la chaîne d'approvisionnement et de la durabilité, il est difficile de considérer toutes les complexités et tous les aspects du problème. Ici, certaines limites de cette contribution seront soulignées afin d'éclairer les travaux futurs qui pourraient en dériver.

1. **Du point de vue des méthodologies utilisées (dynamique des systèmes et optimisation)**, ces méthodologies ont été utilisées avec différentes limitations à savoir :
 - Dans le cas de la dynamique des systèmes, le modèle a été construit pour ne prendre en compte que deux acteurs du système (les installations de recyclage à but non lucratif et les écoles). D'autre part, le système ne prend en compte qu'un seul matériau (un seul déchet d'impression 3D spécifique). Par conséquent, les recherches futures pourraient prendre en compte d'autres acteurs possibles qui pourraient participer au système étudié (par exemple, les installations de recyclage à but lucratif et les utilisateurs privés d'impression en 3D), ceci demanderait une pré étude sur le modèle économique à mettre en oeuvre. De plus, les travaux futurs pourraient prendre en compte différents types et sources de déchets et de mélanges de matériaux. Ceci impliquerait la prise en compte d'autres complexités du processus (tri, nettoyage et décontamination).
 - Pour ce qui est du modèle d'optimisation développé, il ne considère qu'un seul objectif, une seule période, un seul type de matériau et ne considère que la maximisation des aspects économiques et environnementaux (dans une seule fonction objective). Les recherches futures pourraient développer des modèles plus robustes qui considèrent différents critères de durabilité (établis dans cette recherche) dans différentes fonctions objectives. De cette façon, les objectifs de différents décideurs pourraient être pris en compte.
2. **Du point de vue de l'évaluation des impacts sur l'écosystème**, l'approche de recyclage doit être étudiée d'avantage, par exemple, en considérant les services écosystémiques. Plus précisément, l'impact négatif que les déchets plastiques ont sur la biodiversité (en particulier dans la mer) et sur la santé humaine en raison des additifs utilisés dans leur production est bien connu. Par conséquent, l'impact évité (ou non évité) sur les services écosystémiques grâce à cette approche de recyclage serait une évaluation pour de futures recherches

3. **Considérant le cadre d'évaluation** proposé dans cette recherche, il n'a été utilisé que d'une seule manière. Plus précisément, la couche opérationnelle a été explorée en premier, puis les résultats obtenus ont été utilisés dans la couche système (voir Fig. 9). L'expérience acquise dans le cadre de cette recherche nous a permis de conclure que la manière dont la méthodologie doit être appliquée dépend de la disponibilité des données, ainsi que du profil du modélisateur (profil systémique, profil opérationnel ou les deux). Par conséquent, une manière standard (mais adaptée aux besoins du modélisateur) d'appliquer les deux méthodologies dans l'évaluation des chaînes d'approvisionnement pourrait être abordée dans de futures recherches.
4. **Du point de vue de l'application** : l'application et la faisabilité de cette approche de recyclage peuvent varier en fonction du contexte (comportement des citoyens, politiques, etc.). Afin d'étudier ce dernier point, de futures recherches pourraient appliquer cette méthodologie dans différents territoires afin d'analyser la faisabilité de cette approche de recyclage dans différents contextes.
5. Si nous considérons le schéma proposé dans la figure. 1, nous n'avons jusqu'à présent considéré que des "déchets plastiques propres". Un travail important doit être effectué sur les phases de préparation (Fig. 1) afin de permettre un recyclage local plus important des déchets plastiques. Pour ce faire, des études plus précises de la taille et nature des gisements potentiels à l'échelle locale, doivent être effectuées.

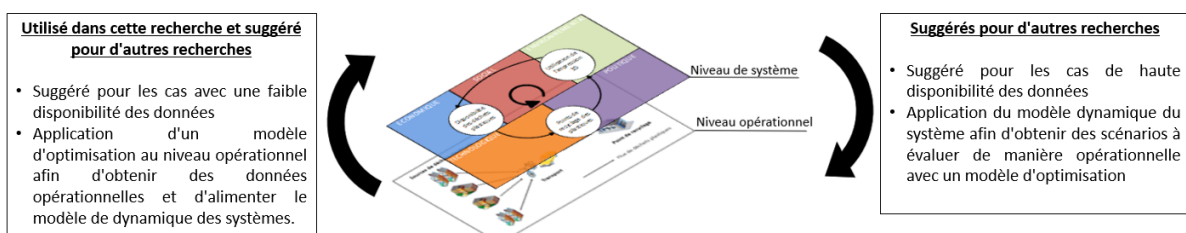


Figure 9. Proposition d'intégration de la dynamique des systèmes et de l'optimisation pour l'évaluation des chaînes d'approvisionnement.

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General Introduction: Why there is need for disruptive organization for plastic recycling?

Today, our society faces important challenges in order to achieve a more resource efficient and climate change resilient society. These objectives require economic, social, organizational and technological changes⁶. Plastic use, transformation and disposal is a major issue that is yet to be solved from the perspective of more sustainable development of human activities. Although, a significant amount of used plastic material could be potentially recycled⁷, considering the plastic generated since 1950, only 9% has been recycled worldwide [1]. Plastic for change⁸ states that the low recycling rates are due to six factors: (1) Lack of household collection and segregation, (2) Competition with virgin⁹ plastic, (3) Volatility in the commodity value, (4) Access to capital, (5) Lack of advanced processing technology and (6) Education in relation to plastic recycling (from consumer to manufacturer). Therefore, the way to address the problem of plastic recycling needs a global vision under sustainability considerations. Once, recognizing that the first measure should be reducing the use and consumption of plastics, the current low plastic recycling rates, motivates the search for new options of valorization in order to increase its recycling rate and contribute to the socio-environmental challenges around this material. In this sense, since the recent years the distributed plastic recycling using 3D open source technologies has emerged in the scientific community as a possible option for the valorization of plastic waste. However, there are still a lot of questions to be addressed before considering it as a relevant solution. In the following sections, an overview of distributed plastic recycling using 3D open source technologies is presented, in order to allow the reader to understand the context, goals and organization of this research.

The plastic problem and the obstacles of the current plastic recycling paradigm

Plastic is a widely used material in the manufacture of a wide variety of products present in our everyday lives. As a result of this, the quantity of plastics manufactured in 2016 was close to 335 million tons in the world, and 60 million tons in Europe alone. Disposal and reuse of these materials is currently one of the main challenges that are part of the recent environmental policies in developed countries¹⁰. However, the amount of plastics which are recycled remains very low. For example, in Europe (that is supposed to be the most advanced

⁶ CORDIS, "SOCIETAL CHALLENGES - Climate action, Environment, Resource Efficiency and Raw Materials," 2014. [Online]. Available: <https://cordis.europa.eu/programme/id/H2020-EU.3.5>. [Accessed: 21-Aug-2020]

⁷ Recycling: Reprocessing of the waste materials for the original purposed products or for other purposes [250].

⁸ Plastics for change, "Why are plastic recycling rates so low?," 2017. [Online]. Available: <https://www.plasticsforchange.org/blog/category/why-are-plastic-recycling-rate-so-low>. [Accessed: 21-Aug-2020].

⁹ Virgin material: Previously unused raw material, such as copper, aluminium, lead, zinc, iron, or other metal or metal ore. (Oxford University Press. [Online]. Available: <https://www.oxfordreference.com/view/10.1093/oi/authority.20110803120009679#:~:text=1%20Any%20undeveloped%20resource%20that,Dictionary%20of%20Environment%20and%20Conservation%20%2%BB.>)

¹⁰ EU Comission, "A European Strategy for Plastics in a Circular Economy," 2018.

region on recycling programs) only 14% of the plastic produced was recycled in 2016 ¹¹ [2], [3]. More specifically, considering the collected plastic (27.1 mt) and recycled plastic (31.1% of collected plastic), plastic packaging (PE-LD, PE-LLD, PE-HD, PE-MD, PP, PET) corresponds to the most recycled plastic (6.8 mt, 25.2% of collected plastic or 11.3% of plastic produced) ¹¹.

Indeed, under the current industrial paradigm, the plastic recycling process is generally carried out through centralized networks¹² in order “to take advantage of economies of scale in producing low value commodities” [14]. However, this approach must face the challenge of sorting, collection and transportation for very heterogeneous type of low density materials, in addition to requiring large capital and operating investments [14]–[16]. This situation makes the recycling of plastic non economical, nor environmentally friendly under this centralized approach [14]–[16].

The above presented antecedents have caused great concern due to their economic, environmental and social impacts. In economic terms, it is estimated that 95% of the value of plastic packaging is lost annually¹³. In environmental terms, it is projected that by 2025 there will be an equal weight of fish and plastics in oceans, and by 2050, the proportion of plastics will be even greater¹³. From the social point of view, among other effects, these environmental issues could have negative effects on human health due to the chemical components and additives used in the manufacture of plastics¹³. Therefore, there is an urgent need to reduce the quantity of used plastics, but also to improve their recycling rate significantly. One promising way to face the plastics problem is the implementation of Circular Economy (CE) oriented approaches. CE is a concept that is gaining increasing attention in Europe and around the world as a potential way for our society to increase prosperity, while reducing dependence on primary materials and energy. Saidani et al. [17] state that CE corresponds to the opposite of the linear model “take-make-dispose.” Moreover, Geissdoerfer et al. [17] define the CE as “a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops.” The goal of the circular economy concept then is to “have an integrated process between technical and biological flows and an integrated management by minimizing or eliminating waste” [18]. Indeed, one of the main characteristics of the Circular Economy is the strong emphasis on closed and local loops, promoting maintenance, reuse¹⁴, remanufacturing¹⁵ and recycling [17].

In order to face today’s plastic problems, the European Union has begun to propose a strategic vision in order to achieve a circular economy for plastic material¹⁶. Based on this strategic vision, different objectives have been proposed for achievement by the year 2030. For example, more than half of the plastic waste generated will have to be recycled, and all plastic packaging marketed in the European Union will have to be reusable or recyclable in a cost-effective manner¹⁶. The French government in particular has defined a goal towards 100% of plastics recycling by 2025, based on the circular economy, leading to a significant reduction

¹¹ PlasticsEurope, “Plastics-the facts 2017, An analysis of European plastics production, demand and waste data,” 2017.

¹² System of interdependent processes, where actions in one part affect those of all others [251].

¹³ World Economic Forum, Ellen MacArthur Foundation, and McKinsey & Company, “The New Plastics Economy — Rethinking the future of plastics,” 2016

¹⁴ Reuse: Extension of usable lifespan of equipment to a secondary market [250].

¹⁵ Remanufacturing: Production-batch process in which used products or cores are disassembled, cleaned, repaired or refurbished, reassembled and qualified for new or like-new equipment’s [250].

¹⁶ EU Comission, “A European Strategy for Plastics in a Circular Economy,” 2018.

of greenhouse gas emissions¹⁷. It is therefore urgent to explore new ways to recycle plastic to attain these ambitious objectives and avoid the environmental risks linked to plastic disposal.

Emergence of 3D printing (Fused Deposition Modeling): A new option for the revalorization of plastic waste

The development of Additive Manufacturing (AM) technology is opening up opportunities in the plastic recycling context. AM, also known as 3D printing (3DP), is a technology that has undergone great development in recent years. AM is defined as “a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”¹⁸. Fused Deposition Modeling (FDM) is one of the seven techniques developed in AM technology¹⁸. FDM uses the extrusion process, where a thermoplastic filament is melted and deposited in a predefined way to generate the product. The simplicity of the process in the FDM makes the needed equipment relatively inexpensive. In addition, the raw materials¹⁹ used are low-cost, low toxic (under certain space and ventilation conditions [19]), and odorless, making it ideal for the hobbyist. The most used materials in FDM are ABS (Acrylonitrile Butadiene Styrene), PLA (Polylactic Acid), and PC (Polycarbonate) [20], [21].

The patent expiration of the FDM technology in the mid 2000's allows users to develop this technology in an Open Source (OS) noncommercial way, enabling a decrease in the acquisition costs of this technology and making it accessible to all [22]. An example of this is the RepRap project, which allows users to acquire a 3D printer in the range of \$200 to \$500, and it is estimated that between 2008 and 2011 the number of RepRaps models of machine increased from four to 4,500 [14]. Today, among the seven AM technologies, material extrusion-based systems using thermoplastic materials such as Fused Filament Fabrication (FFF) (and its relative commercial option Fused Deposition Modelling (FDM)) are the most extended [23].

The rapid growth of this OS technology has motivated different researches exploring a disruptive recycling paradigm based on the notion of distributed manufacturing and distributed recycling, by opposition to the centralized network model, in order to valorize plastic waste using 3D OS technologies [14], [24]–[29]. Among the plastic materials explored, it is possible to find studies that consider the use of: polyethylene terephthalate (PET), high-density polyethylene (HDPE), linear low density polyethylene (LLDPE), low density polyethylene (LDPE), poly-propylene (PP), polystyrene (PS), polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), thermo-plastic elastomer (TPE) and biomass-derived poly(ethylene-2,5-furandicarboxylate) (PEF) [4].

Distributed manufacturing and Distributed recycling: A new paradigm of plastic recycling network

In order to tackle the above-mentioned environmental complexities around plastic waste, and to demonstrate the sustainability benefits of the recycling process, the notion of Distributed Manufacturing and its reciprocal Distributed Recycling, supported by commercial

¹⁷ MTES, “50 mesures pour une économie 100% circulaire,” 2018

¹⁸ ASTM and ISO, “Standard Terminology for Additive Manufacturing – General Principles – Terminology,” *Iso/Astm*, vol. 52900. p. 9, 2015

¹⁹ Raw material: Any material in its natural condition, before it has been processed for use. (“Cambridge Dictionary.” [Online]. Available: [https://dictionary.cambridge.org/dictionary/english/raw-material.](https://dictionary.cambridge.org/dictionary/english/raw-material))

and open-source (OS) 3D printers, has progressively emerged in the scientific literature. Distributed manufacturing has been defined as a form of decentralized local production developed thanks to the synergy among emerging digital fabrication capabilities, information and communication technologies, and the commons-based peer production approach (e.g. the self-selection of tasks by the participants, modularity design) [30], [31]. Distributed manufacturing offers the potential to decentralize production structures, the flexibility to reflect local customers' needs, lower logistics costs, shorter delivery times and reduced environmental impacts²⁰ [28], [32]. More precisely, from a supply chain perspective, 3D printing has a widespread expectation to promote a number of structural changes (e.g. inventory reductions [33], [34], reduce disassembling efforts [34], on-demand spare parts [34], [35], customization and personalization [33], [34], [36], decentralized production close to the consumers [33], [34], [36], or even reduce the labor input needed for production [34], [37]). Matt et al. [32], examined the different types of distributed manufacturing models. They have shown that the most basic form of distributed manufacturing consists of the geographical distribution of factories to produce defined and standardized products. The most advanced form considers the use of Additive Manufacturing or 3D printers, where the provider does not sell the physical product but rather the product data, which could then be manufactured and assembled in distributed networks of printing labs or small factories with high-performance printers and qualified staff for final assembly and finishing.

Indeed, as OS 3D printers improve progressively in performance, reliability, and material options, and decline in cost, these devices would play an important role in the deployment of distributed manufacturing. Considering FFF technology, Kreiger & Pearce [28] worked on the evaluation of the environmental impact of distributed manufacturing of polymer products made with OS 3D printers. Their results showed that distributed manufacturing requires less cumulative energy than conventional (centralized) manufacturing. Moreover, by joining 3D printing capabilities with the photovoltaic grid, the impact could be even less. From an economic point of view, Wittbrodt et al. [29] proved the attractiveness of this technology for an average US household, up to the point that it could become a mass-market mechatronic device. However, as the AM technology (and in particular FFF) will continue to grow in the years to come, probably the polymer waste will continue to be disposed anywhere.

On the other hand, the development of the open-source (OS) waste plastic extruder, which produces the filament for 3D printing, offers improved environmental and economic performance of distributed plastic recycling [28], [29], [38]. This emerging recycling could be carried out in distributed facilities and on a local scale (city, town, or neighborhood) by means of 3D open-source technologies. For example, Zhong & Pearce [39] demonstrated that the coupling of an open-source recyclebot (open source extruder) and RepRap 3D printer “*brings a traditional industrial system into a small single home, business or community center*”. In addition, different studies in the literature show the technical feasibility²¹ of this distributed plastic recycling approach [14], [24]–[27]. In fact, the literature review conducted by Cruz Sanchez et al. [4] on distributed plastic recycling for 3D printing has shown that most of the already existing studies have been concentrated on the compounding, feedstock and printing stages of the process (See Figure 0.1), while the recovery and preparation stages have been less studied. This fact, underlines the lack of development to implement a complete domain

²⁰ Environmental Impact: The effect that the activities of people and businesses have on the environment. (“Cambridge Dictionary.” [Online]. Available: <https://dictionary.cambridge.org/dictionary/english/environmental-impact>.)

²¹ Feasibility: The possibility that can be made, done, or achieved, or is reasonable. (“Cambridge Dictionary.” [Online]. Available: <https://dictionary.cambridge.org/dictionary/english/feasibility>.)

of recycling. Nevertheless, the notion of open source (OS) makes it possible to create technically superior and far less expensive equipment than proprietary models [5], [6]. Therefore, with this recycling approach, the economic and environmental problems inherent to centralized plastic recycling networks are likely to be mitigated, mainly due to the use of lower-cost OS technology, short recovery distances, and low-quantity transportation of plastic waste.

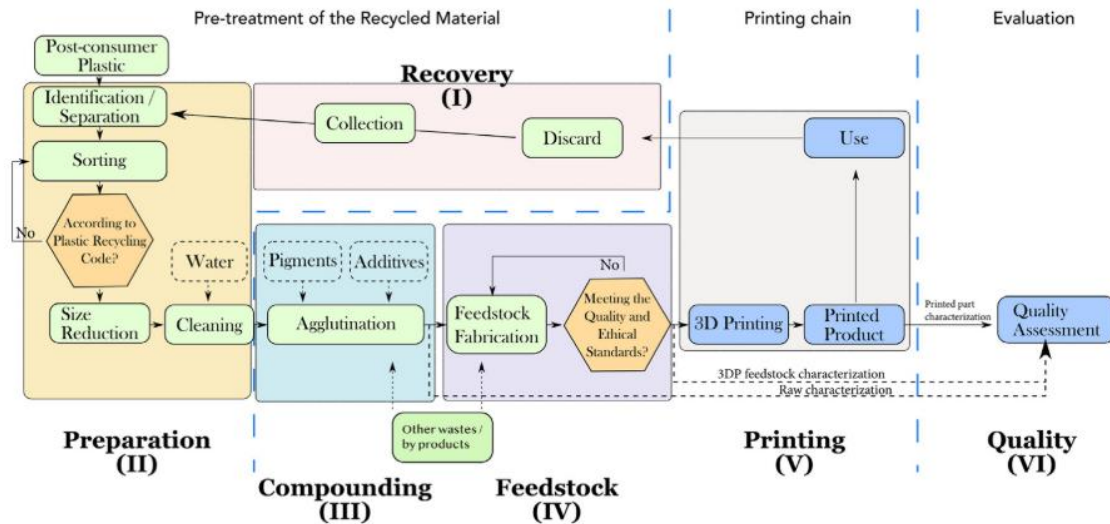


Figure 0.1. Technological stages of distributed plastic recycling for 3D printing (Source: Cruz Sanchez et al. [4]).

The previous studies allow us to infer that the 3D based recycling activity will emerge mainly as local user-driven initiatives and not necessarily as a formal structured industrial sector, as the plastic recycling networks have normally been addressed until now. As a consequence, we can conclude that recycling for 3D printing taps into economies of scope (or niche) rather than scale [15]. Nevertheless, this approach to distributed plastic recycling also presents some technical, social and economic complexities, barriers and challenges, which must be addressed [15], [40]. From a technical perspective, the great variety of thermoplastics with different properties and their lack of specificity in the categories, are identified important barriers [40]. The uncertainty regarding the quantity and composition of plastic waste, the quality of the printed product (regardless of whether the plastic is virgin or recycled) and “the limited availability and efficiency of small-scale recycling technologies” are some challenges that should be addressed [15]. Regarding social aspects, elements such as the people custom to consume in a linear system without seeing value in waste and high quality demands of the recycled filament from consumers are important barriers to consider [40]. The people’s willingness to cooperate with the recycling process and to use recycled plastic in 3D printing, but also how to deal with the user-perceived low value of recycled 3D printed products, and their “lack of acceptance of/need to use recycled over virgin materials” are some challenges that should be addressed [15]. Finally, from an economical perspective, the uncertainty about return on investment is a identified barrier [40]. Mastering operating costs and enhancing added value creation for stakeholders of the recycling system is still crucial to justify any recycling process. In addition to the complexities, barriers and challenges mentioned above, the recycling process must be developed in a sustainable way, that is, it must “meets the needs of the present without compromising the

ability of future generations to meet their own needs"²² [41]. From the sustainability evaluation perspective, a system is sustainable, if it integrates the economic, environmental and social dimensions, traditionally referred to as the three pillars of sustainability ('triple bottom-lines - TBL) [7]. Furthermore, Bautista et al. [8] proposes the integration of political and technological dimensions (TBL+) if they have a great importance in the system under evaluation. Considering the large number of elements to be taken into account, which make the system very complex during the evaluation process, evaluation methods and tools are necessary at the early stages of the project in order to analyze its impacts. In this way, stakeholders can reach consensus in order to make the best possible decisions prior to implementation (or non-implementation). Considering that the literature on distributed plastic recycling has proven the feasibility of this paradigm from a technical point of view [4], its feasibility from the supply chain/logistical point of view still needs to be demonstrated. In order to tackle this issue, this research thesis seeks to provide answers to the following research question: Under which conditions is it possible to deploy a sustainable local and distributed plastic recycling network using open source 3D printing technologies? Considering the above, this research work aims to propose a framework for the analysis and evaluation, from the point of view of sustainability, of the distributed plastic recycling approach for 3D printing. Thanks to the modeling of complex systems, the decision-making process of emerging recycling supply chains could be supported.

Research goal

The overall goal of this research is the proposition and evaluation of a sustainable, distributed and local plastic recycling network in the context of the circular economy using 3D Open Source technologies.

The main contributions of this thesis can be summarized as follows:

- A detailed bibliographic analysis of sustainable plastic recycling networks.
- A detailed bibliographic analysis of political, social and technological dimensions in the evaluation of sustainable recycling networks.
- Proposition of a two-level modelling approach for distributed plastic recycling using 3D open source technologies.
- Formalization of the distributed plastic recycling network from the operational/logistic point of view.
- Formalization of the distributed plastic recycling network from the system point of view.

Organization of the thesis

This thesis is organized as depicted in Figure 0-2. Each chapter is presented below.

²² G. H. Brundtland, "Report of the World Commission on Environment and Development: Our Common Future," Oslo, 1987.

Chapter I. A sustainable plastic recycling network: A literature review. First, in order to explore how plastic recycling networks have been studied in the literature, a systematic literature review is conducted. The aim is to analyze how the literature has addressed this issue from the point of view of network structure, plastic products/materials, methodology and sustainability dimensions. Through this systematic process, 458 research articles were found and revised. Among them, the most significant references were selected, where 57 references have been selected and analyzed. As main conclusions of the analysis, it has been observed that the plastic recycling networks studied in the literature have a centralized orientation (the distributed approach has not been explored). On the other hand, considering their sustainability evaluation, the social, technological and political dimensions of sustainability have been little considered.

Chapter II. Social, political and technological dimensions for the sustainability evaluation of recycling networks. A literature review. The results of the literature review conducted in the previous chapter has shown that the social, political and technological dimensions of sustainability have been seldom considered in the context of plastic recycling networks. For this reason, this chapter explores how these dimensions should be integrated into the evaluation of the plastic recycling approach proposed in this research. To carry out this analysis, a systematic literature review on sustainability evaluation of recycling networks (in general) is conducted. 640 research articles were found and revised. Among them, 129 significant references were selected. From this literature review we extract the main criteria (for social, technological and political dimensions) to be considered in the evaluation of recycling networks.

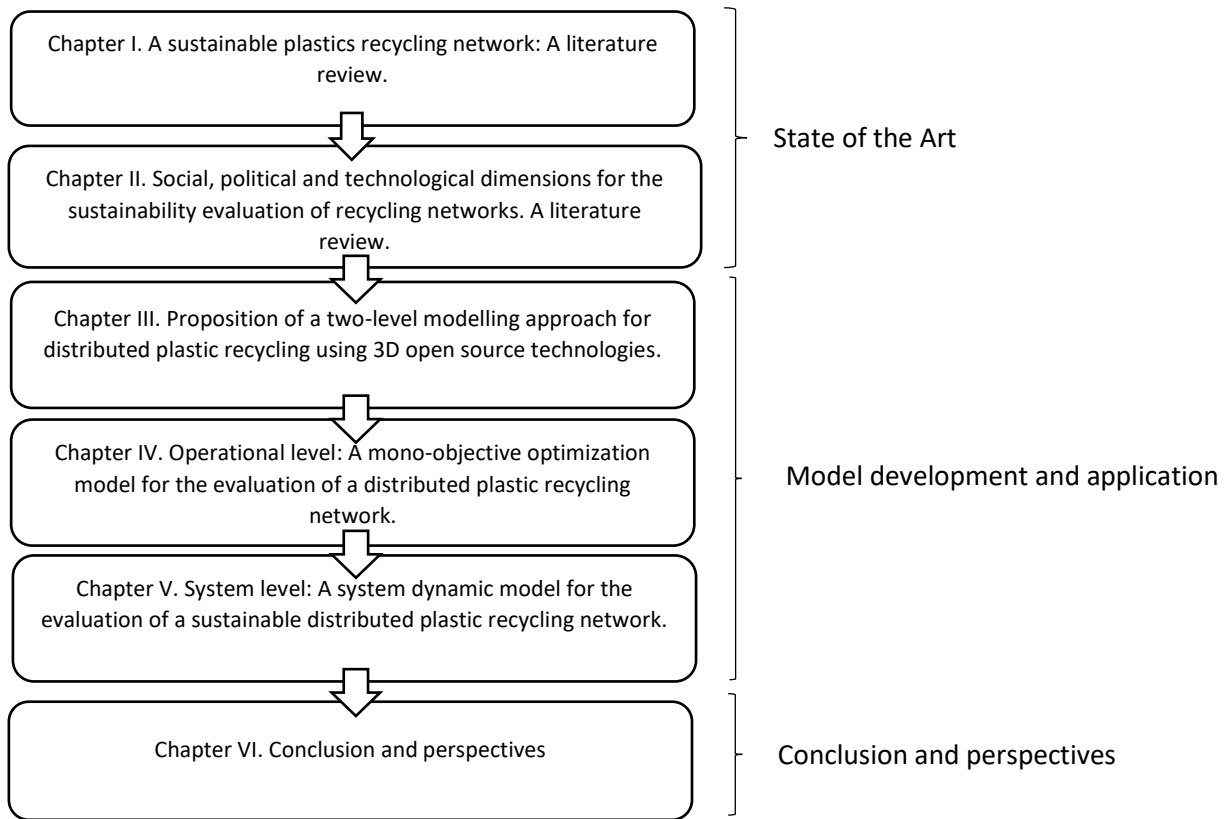


Figure 0.2. Structure of the document

Chapter III. Proposition of a two-level modelling framework for distributed plastic recycling using 3D open source technologies. From the analysis carried out in the previous chapters, the set of most relevant criteria have been obtained for the evaluation of sustainable recycling networks. This chapter presents an analysis of the methodologies used for their evaluation in order to select the appropriate methodology considering the objectives of this research. As a conclusion of the analysis, a two-level modeling framework is proposed for the evaluation of distributed plastic recycling using 3D OS technologies. The modeling approach proposes an analysis from the system point of view (upper layer) and from the operational point of view (lower layer). System Dynamics and Mathematical Optimization are the proposed methodologies for the upper and lower layer respectively.

Chapter IV. Operational level: A mono-objective optimization model for the evaluation of a distributed plastic recycling network. In this chapter, the optimization model developed for the analysis of distributed plastic recycling from an operational/logistic point of view (lower layer of the two-level modelling framework proposed in chapter III) is presented. The model developed is applied to a specific case study. The results of the application are presented and discussed.

Chapter V. System level: A system dynamic model for the evaluation of a sustainable distributed plastic recycling network. In this chapter, the system dynamic model developed for the analysis of distributed plastic recycling from a system point of view (upper layer of the two-level modelling framework proposed in chapter III) is presented. The model developed is applied to the same case study of chapter IV. The results of the application are presented and discussed.

This document finishes then, by presenting the main conclusions and perspectives that synthesize our contribution

This thesis has been financially supported by Ministère de l'Enseignement supérieur, de la Recherche et de l'Innovation -MESRI- (Ministry of Higher Education, Research and Innovation) and Équipe de Recherche sur les Processus Innovatifs -ERPI- (Research Team in Innovative Process) in Nancy, France.

A research paper resulting from the IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) in 2018 was published, and also a scientific paper has been published in Resources, Conservation & Recycling Journal in 2019.

Chapter I. A sustainable plastic recycling network: A Literature Review

1.1. Chapter introduction

Recycling is an activity aimed “to have more raw materials” from used products [42]. If we consider the literature on recycling networks, we can see that, on the whole, two types of networks coexist [42]: Reverse Supply Chain (RSC) (or Reverse Logistic (RL)) and Closed Loop Supply Chain (CLSC) (see Figure I.1). RSC is a network for the recovery of discarded products for recycling or reuse in other products, while CLSC corresponds is a network that integrates and acts at the same time: Forward and Reverse Supply Chain [9], [42]–[46]. The flow of goods from the supplier to the client is undertaken through the Forward Supply Chain, while the Reverse Supply Chain recovers the products from the customer for recycling [9], [42], [43], [45], [47].

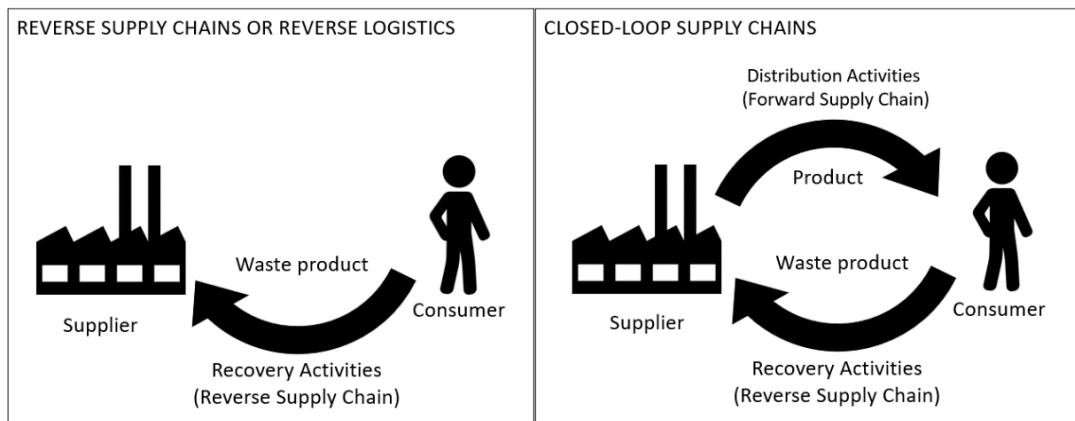


Figure I.1. Reverse and closed loop supply chains in recycling

At the time of exploring and evaluating new plastic recycling networks such as the one proposed in this research, the interests of different actors must be considered, which may come into conflict. For example, a recycling network may be environmentally feasible and economically unfeasible, which directly affects the organization carrying out the activity if its interest is to make a profit. In this area, the concept of sustainability is presented in the literature. As mentioned in the introduction of this thesis, a system is sustainable if it considers economic, environmental, social, political and technological dimensions. Therefore, when evaluating a new plastic recycling network, the five dimensions of sustainability should be considered in the evaluation process. The economic dimension considers all those aspects related to an economically self-sustainable recycling system [8], [48]. The environmental dimension considers the impact (positive or negative) on the environment due to the implementation of the system [8], [48]. Similarly, the social dimension considers the impacts (positive or negative) on society due to the implementation of the system [8], [48]. The political dimension considers the influence of governmental/legal policies (for example, taxes and subsidies or other types of incentives/penalties) on the recycling system [8], [48]. Finally, the technological dimension considers the influence on the system of the technological constraints as well as the development of the technologies used in the system [8], [48].

In this chapter, a systematic literature review has been carried out in order to understand the way in which plastic recycling networks have been studied, by the scientific community, considering the five dimensions of sustainability. The economic dimension considers all those aspects related to an economically self-sustainable system. For example,

1.2. Methodology and data selection

A systematic literature review approach was carried out based on the guidelines of [Siddaway et al. \[49\]](#). [Table I.1](#) details the steps followed for the article selection. Then, a systematic selection of the literature has been carried out. The procedure of articles selection is shown in [Fig. I.2](#).

From the search in the different databases, a total of 458 studies were identified. Among the studies identified, 45 correspond to duplicate studies, leaving a total of 413 articles to be selected. Then, a selection by abstract relevance was carried out, leaving only those documents related to the analysis or evaluation of recycling networks. Only 184 documents passed this filter. Finally, a selection by reading was carried out, selecting only those documents that effectively evaluate or analyze a recycling network and consider plastic material. As result, 57 articles were selected for a deeper analysis.

Table I.1 Systematic review protocol for the literature

Stage	Principle	Description
Search Strategy	Type of studies	Journals and conference papers
	Keywords	Closed-loop supply chains, Reverse Logistics, Reverse supply chains, recycling, plastic, polymer
	Search equation	("Closed-loop supply chain*" OR "Closed loop supply chain*" OR "Reverse Logistic*" OR "Reverse supply chain*") AND (recycl*) AND (plastic* OR polymer*)
	Period of time	Until May 2020
	Databases	Scopus, Springer and Web of Science
Study Selection	Criteria	1) Articles related to the analysis or evaluation of recycling networks 2) Articles that consider plastic material
	Procedure	1) Title, abstract and keywords are screened 2) Full article was reviewed 3) Selection is made based on selection criteria
Data extraction	Network structure, material, methodology and sustainability dimensions	<ul style="list-style-type: none"> • Material/product • Type of supply chain network (RL-RSC or CLSC) • Network type (Centralized or Distributed) • Methodology and • Sustainability dimensions presented

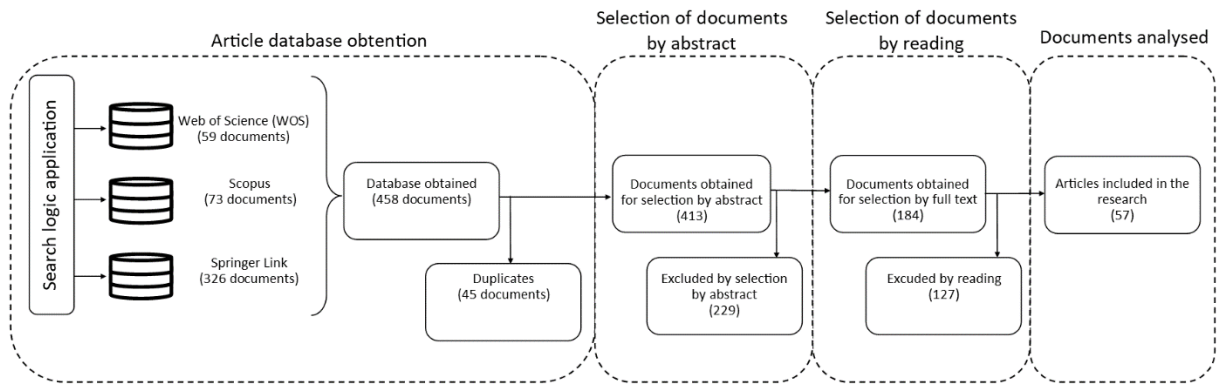


Figure I.2. Systematic document selection about plastic recycling networks

1.3. Descriptive analysis

Figure I.3 shows the ranking of journals with at least two documents considered in this review. On the other hand, Figure I.4 presents the temporal distribution of the selected documents. Globally, a great interest of the literature is observed, from the year 2013, by the study and evaluation of plastic recycling networks.

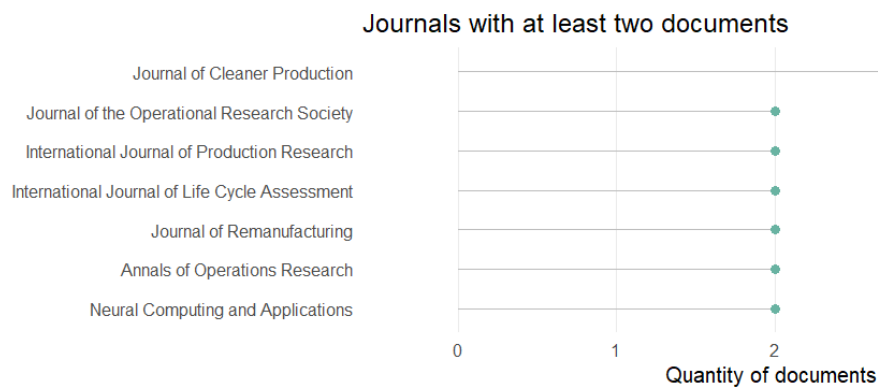


Figure I.3. Ranking of journals with at least two documents

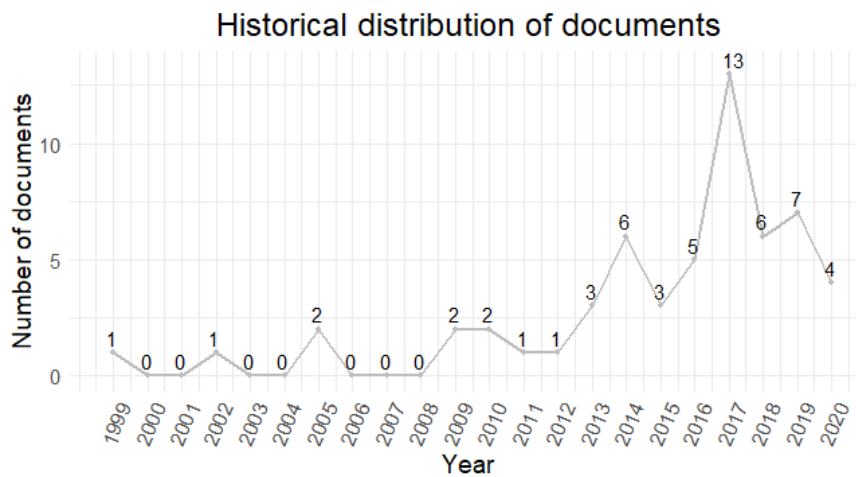


Figure I.4. Historical distribution of selected documents

1.4. Review of literature

The following subsections present a detailed qualitative analysis of plastic recycling network recycling network. After having made the filters described in [section 1.2](#), the articles were analyzed considering two perspectives: (1) from the network structure and product perspective, and (2) from the sustainability evaluation perspective. On the one hand, the network structure and product perspective analyze the paradigms and plastic materials/products considered in the literature on plastic recycling. This analysis is important due to the logistical and technical issues above mentioned regarding the recycling of this material. For this purpose, the articles were analyzed in terms of: (1) Material/product (2) type of supply chain network (RL-RSC or CLSC) and (3) Network type (Centralized or Distributed). On the other hand, the sustainability evaluation perspective was also considered. It analyzes the evaluation methodologies and the sustainability dimensions considered for this purpose. This analysis is performed due to the importance of selecting the appropriate methodology and criteria for the evaluation of a sustainable plastic recycling network. For this purpose, the articles have also been analyzed in terms of: (5) Methodology and (6) Sustainability dimensions presented. [Table I.2](#) shows a summary of the analysis conducted.

Table I.2. Analysis of the 57 publications selected in this study

Reference	Network structure and product perspective			Sustainability evaluation perspective						
	Material/Product	Type of network		Approach	Methodology	Sustainability Dimensions				
		RL-RSC	CLSC			Economical	Environmental	Social	Political	Technological
[50]	PET of car seats		1	Centralized	Evaluation based on PESTLE analysis	1	1	1	1	1
[51]	Plastic in general		1	Centralized	Optimization	1	1		1	1
[52]	Plastic bottles		1	Centralized	Optimization	1	1			1
[53]	PET bottles		1	Centralized	Optimization	1	1			1
[54]	LDPE		1	Centralized	Optimization	1	1			1
[55]	Plastic in general		1	Centralized	Game theory	1	1	1	1	
[56]	Beverage bottles PET		1	Centralized	Inventory Model	1	1			
[57]	Plastic bottles		1	Centralized	Optimization	1		1		1
[58]	Disposable tableware		1	Centralized	Optimization	1				1
[59]	Plastic water cane		1	Centralized	Optimization	1				1
[60]	Plastic pallets		1	Centralized	Optimization	1				1
[61]	Plastic in general		1	Centralized	Optimization	1				1
[62]	Nylon plastic		1	Centralized	Optimization	1				1
[63]	Plastic in general		1	Centralized	Game theory	1		1		
[64]	Plastic in general		1	Centralized	Game theory	1		1		
[65]	Plastic in general		1	Centralized	Optimization	1				
[66]	Aseptic carton packages	1		Centralized	Discrete event simulation	1	1	1		1
[67]	Plastic in general	1		Centralized	Optimization and Life Cycle Analysis	1	1	1		1
[68]	MSW	1		Centralized	Optimization	1	1	1		1
[69]	Carbon fiber reinforced polymers	1		Centralized	Optimization	1	1			1
[70]	Plastic in general	1		Centralized	Optimization	1	1			1
[71]	EOL product	1		Centralized	Optimization	1	1			1
[72]	Plastic in general	1		Centralized	Optimization	1	1			1
[73]	Plastic in general	1		Centralized	Optimization	1	1			1
[10]	Plastic in general	1		Centralized	Optimization	1	1			1

Table I.2. Analysis of the 57 publications selected in this study (Continuation)

Reference	Network structure and product perspective			Sustainability evaluation perspective						
	Material/Product	Type of network		Approach	Methodology	Sustainability Dimensions				
		RL-RSC	CLSC			Economical	Environmental	Social	Political	Technological
[74]	Plastic in general	1		Centralized	Fuzzy SWARA and fuzzy MOORA	1	1	1	1	
[75]	Computer peripherals products	1		Centralized	Financial Analysis	1	1	1		
[76]	Plastic in general	1		Centralized	Wuppertal method	1	1	1		
[77]	Plastic in general	1		Centralized	Hybrid BSC-DEA (balanced scorecard - data envelopment analysis)	1	1	1		
[78]	WEEE	1		Centralized	Cost evaluation	1	1		1	
[79]	Plastic in general	1		Centralized	Optimization	1	1		1	
[80]	Plastic bottles	1		Centralized	Cost analysis and Life Cycle Analysis	1	1			
[81]	Plastic bottles	1		Centralized	Process-based cost modeling method (PBCM)	1	1			
[82]	Plastic in general	1		Centralized	Optimization	1		1	1	1
[83]	WEEE	1		Centralized	Optimization	1			1	1
[84]	Plastic in general	1		Centralized	Optimization	1				1
[85]	Plastic in general	1		Centralized	Optimization	1				1
[86]	Plastic carpets	1		Centralized	Optimization	1				1
[87]	Plastic bottles	1		Centralized	Optimization	1				1
[88]	Polyethylene	1		Centralized	Optimization	1				1
[89]	Plastic in general	1		Centralized	Optimization	1		1		
[90]	Polymer packaging	1		Centralized	Cost analysis based on RL mapping	1				
[91]	Plastic container	1		Centralized	Discrete event simulation	1				
[92]	LDPE and HDPE	1		Centralized	Optimization	1				
[93]	Plastic in general	1		Centralized	Cost analysis	1				
[94]	Plastic in general	1		Centralized	Life Cycle Analysis and Simulation		1	1		1
[95]	WEEE plastic (ABS and HIPS)	1		Centralized	Life Cycle Inventory		1			1
[96]	Oil Plastic Containers	1		Centralized	Life Cycle Inventory		1			1
[97]	PET bottles	1		Centralized	Life Cycle Inventory		1			
[98]	Plastic in general	1		Centralized	Wuppertal method		1			
[99]	MSW	1		Centralized	Simulation		1			
[100]	Plastic in general	1		Centralized	Optimization		1			
[101]	Plastic in general	1		Centralized	Wuppertal method		1			
[102]	polystyrene	1		Centralized	Life Cycle Assessment (LCA) and Emergy Analysis (EMA)		1			
[103]	Plastic in general	1		Centralized	Estimation of greenhouse gases		1			
[104]	MSW	1		Centralized	Optimization					
[105]	MSW	1		Centralized	Spatial Analysis					
Total		41	16			45	34	15	8	30

The following subsections present the results obtained. First the analysis network structure and product perspective is presented. Then, the analysis from the sustainability evaluation perspective is presented.

1.4.1. From the network structure and product perspective

Figure I.5 summarizes the results obtained in terms of recycling approach, type of network and material/product considered.

Taking into account the recycling approach of the studies, Figure I.5 shows that all selected documents have considered a centralized approach of recycling (recycling in large quantity with industrial orientation). Regarding the type of network studied, the majority of the studies (72% specifically) consider networks type RL-RSC (41 of the 57 documents selected). Regarding material/product, it can be seen that most of the studies consider the plastic in a general way, that is, without specifying the product or material to be recycled. If the product is specified, the treatment of plastic bottles corresponds to the most considered product. Finally, Figure I.5 shows that, among the most considered products (plastic in general, plastic bottles), most of them consider networks type RL-RSC.

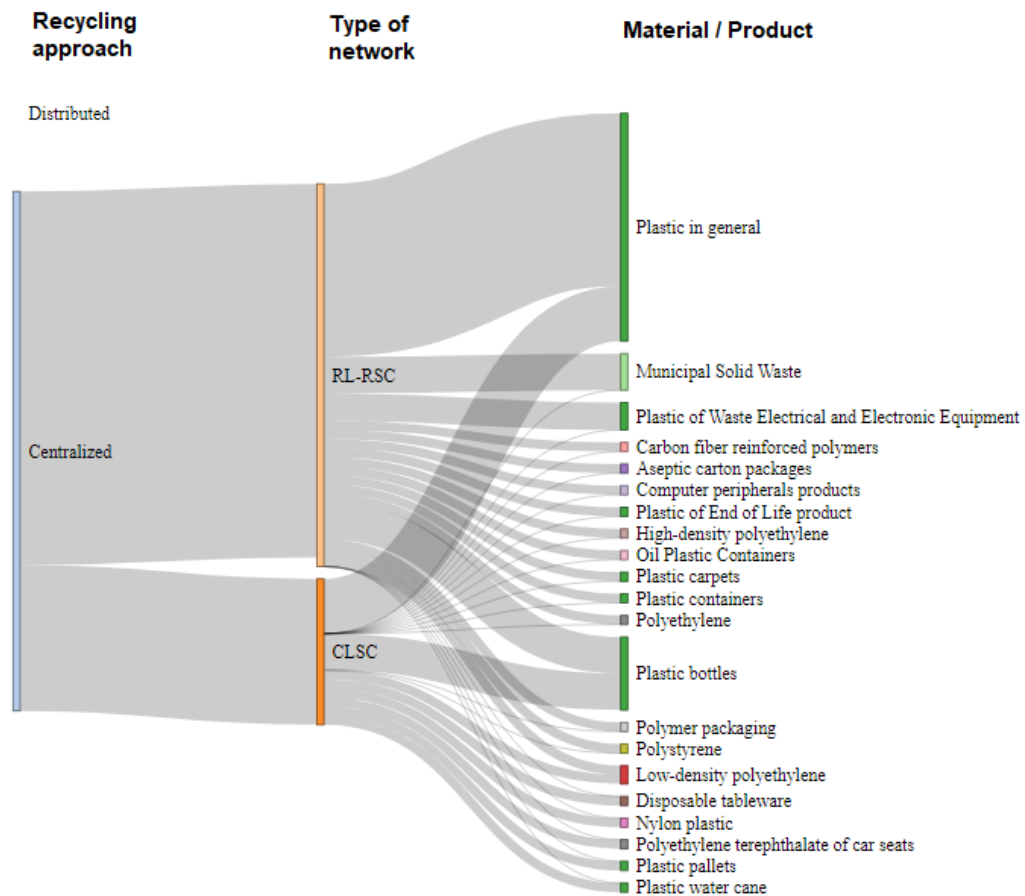


Figure I.5. Summary of results from the point of view of network structure and material/product considered

1.4.2. Sustainability evaluation perspective

In relation to the most applied methodologies by the scientific community, Figure I.6 shows the distribution of the identified methodologies. Optimization corresponds to the most considered, being used in 31 documents. Among the optimization models applied, it is possible to find Multi-objective models ([51], [53], [62], [67], [69], [71], [72], [84], [89]) and Mono-objective Mixed Integer Programming models ([52], [54], [57], [58], [60], [61], [65], [68], [70], [73], [83], [85]–[88], [92], [100], [104], [106]). On the other hand, it is also possible to identify methodologies associated with environmental assessments: Life Cycle Analysis and Wuppertal method.

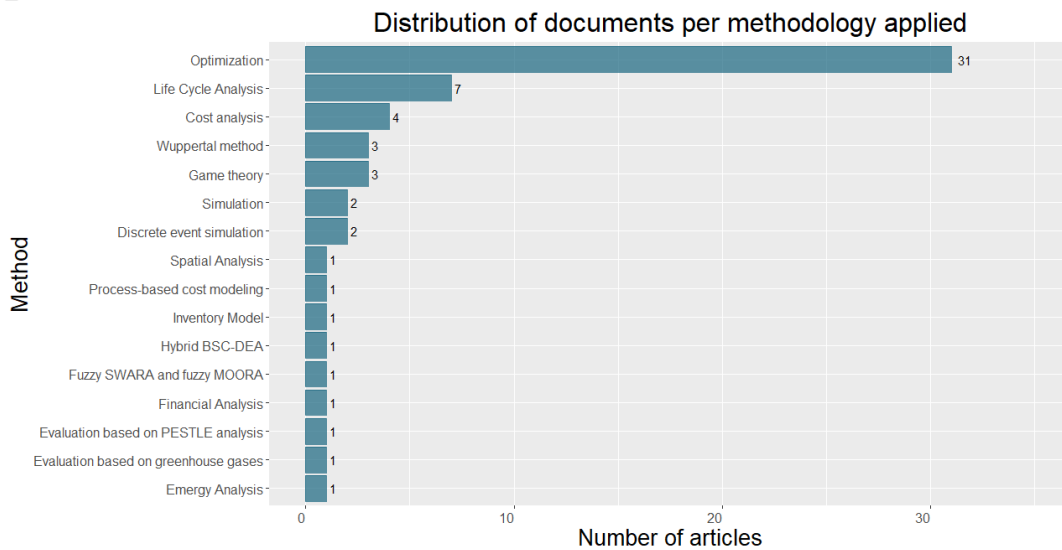


Figure I.6. Distribution of documents considering methodology applied.

In relation to sustainability dimensions, Figure I.7 shows the number of documents in which each of the five dimensions of sustainability has been considered. According to the analysis carried out, the economic, environmental and technological dimensions correspond to the most considered.

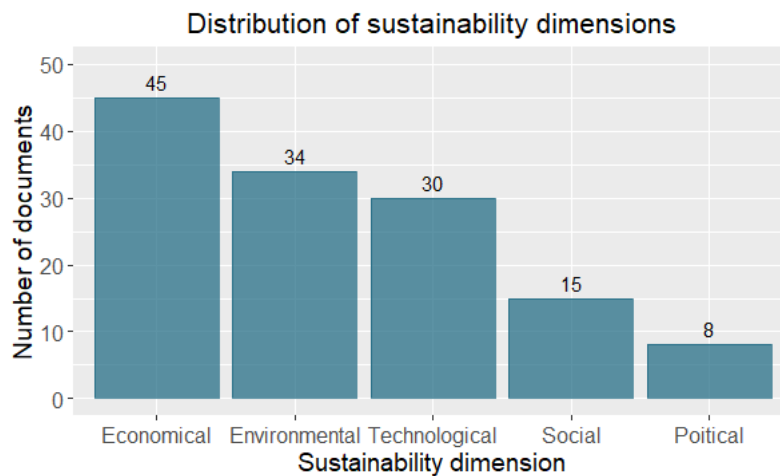


Figure I.7. Distribution of sustainability dimensions considered.

Regarding the consideration of sustainability dimensions simultaneously, [Figure I.8](#) shows the number of documents that simultaneously consider different sustainability dimensions.

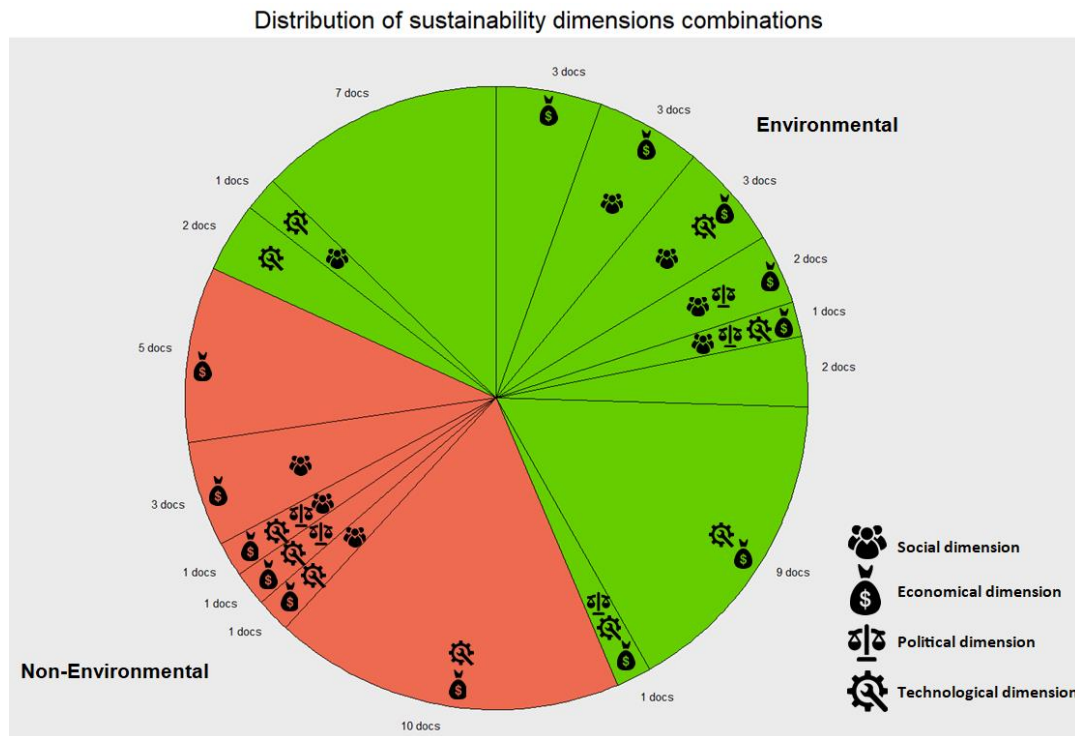


Figure I.8. Distribution of sustainability dimensions combinations.

As can be seen in [Fig I.8](#), most documents combine two dimensions (18 documents) or three dimensions (17 documents) of sustainability. Considering the combination of two dimensions, most documents consider the economic and technological combination (27 documents). Regarding the combination of three dimensions, the consideration of economic, technological and environmental dimensions corresponds to the most considered (9 documents). On the other hand, only 7 documents consider four dimensions of sustainability simultaneously, among which the consideration of the economic, environmental, social and technological dimensions corresponds to the most frequent (3 documents). Finally, only one document considers the five dimensions of sustainability ([Chavez & Sharma \[50\]](#)), who evaluated and compared the profitability and environmental friendliness of a CLSC chemical PET recycling network.

[Fig I.9](#) shows the distribution of articles considering the sustainability dimensions combination and methodology used. As can be seen in [Fig I.9](#), optimization (which has been the most used methodology) has been used mainly for the integration of (1) the economic, environmental and technological dimensions (9 documents), and (2) the economic and technological dimensions (10 documents). However, it has also been used for other combinations, where it has been possible to identify the political ([\[82\]](#), [\[79\]](#), [\[51\]](#), [\[83\]](#)) and social ([\[82\]](#), [\[57\]](#), [\[67\]](#), [\[68\]](#), [\[89\]](#)) dimensions.

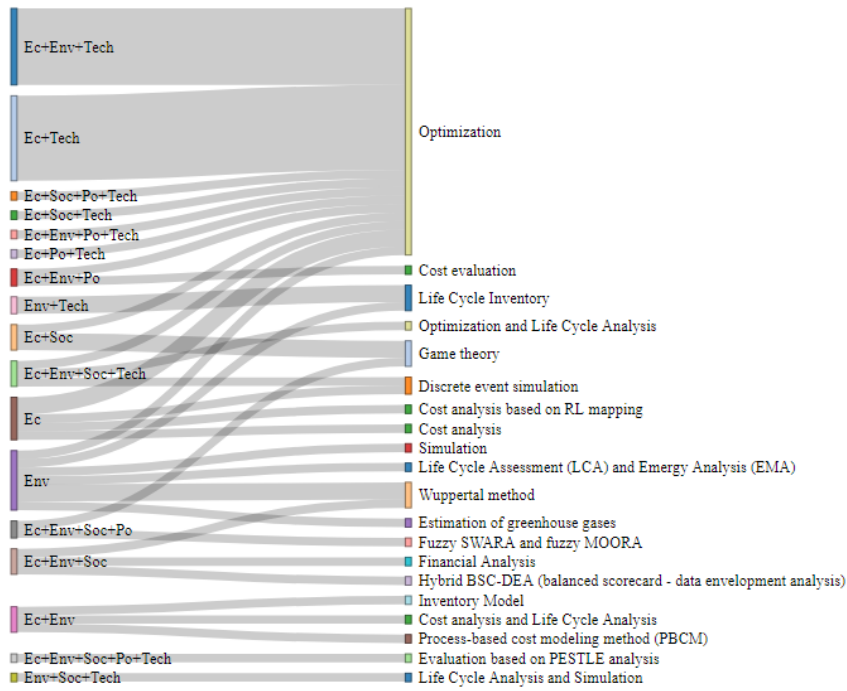


Figure I.9. Distribution of sustainability dimensions combination and methodology used.

An important aspect in the evaluation of a recycling network from a sustainability point of view is its evaluation criteria. Appendix I.1 shows the criteria identified in the analysis for the economic, environmental, social, political and technological dimensions. Figure I.10 shows quantitatively the number of criteria identified for each dimension.

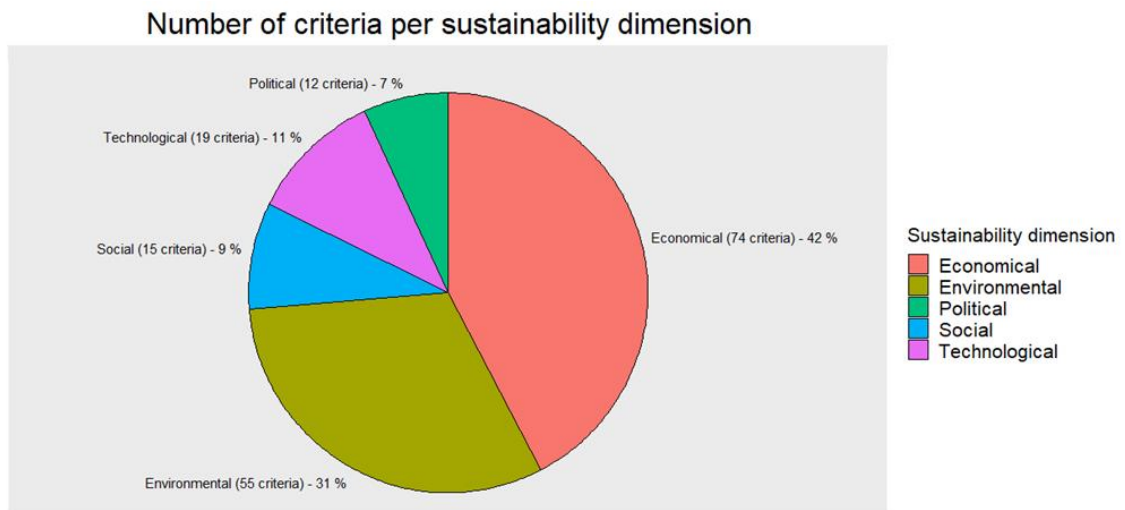


Figure I.10. Number of criteria per sustainability dimension

As can be observed in Figure I.10, most of the criteria identified in the literature on the evaluation of plastic recycling networks are oriented towards the economical (42%) and

environmental (31%) dimensions. On the other hand, a small number of criteria oriented to the social, technological and political dimensions have been identified.

Considering the criteria identified, [Figure I.11-15](#) show the distribution of criteria for the economic, environmental, social, technological and political dimensions (see [Appendix I.1](#) for references). As can be seen in [Figure I.11](#), the economic dimension is considered mainly from the point of view of costs. The most frequently considered costs correspond to these of transport, collection, recycling, processing and facility opening costs. In the environmental dimension ([Fig II.12](#)), carbon emissions and CO₂ emissions are the most frequent criteria. In this dimension, it is possible to find a large number of criteria due to their consideration by means of Life cycle inventory analysis, a methodology that contains a large number of environmental criteria. In the social dimension ([Fig II.13](#)), the consumer's sensitivity corresponds to the most frequent aspect, although it has only been considered in 3 documents. For the political dimension ([Fig II.14](#)), each document has considered this aspect in a different way, among which it is possible to identify, taxes, legal context, government impositions and penalties. Finally, for the technological dimension ([Fig II.15](#)), aspects related to the capacity of the network facilities and the capacity of the means of transport used correspond to the most considered aspects.

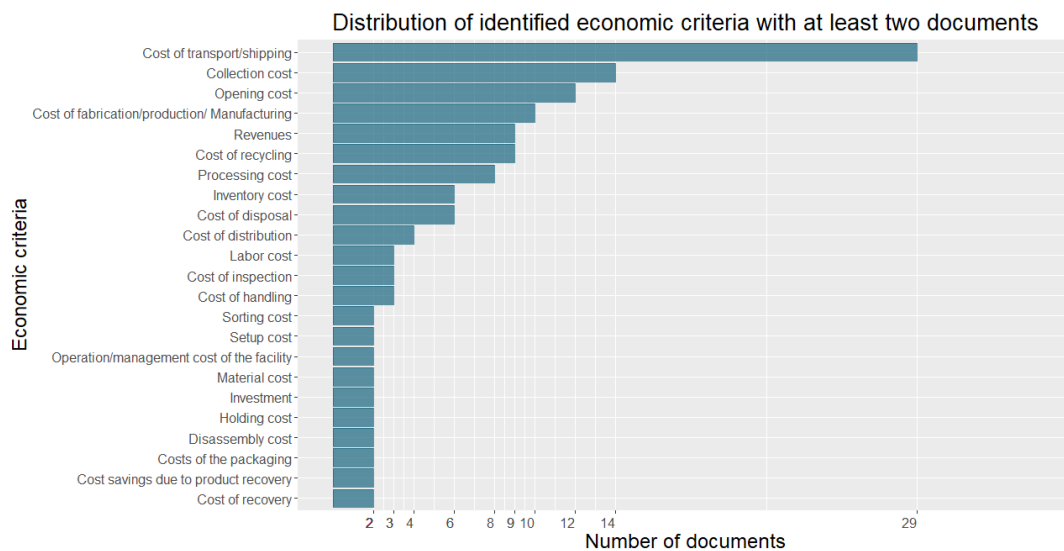


Figure I.11. Distribution of identified economic criteria with at least two documents

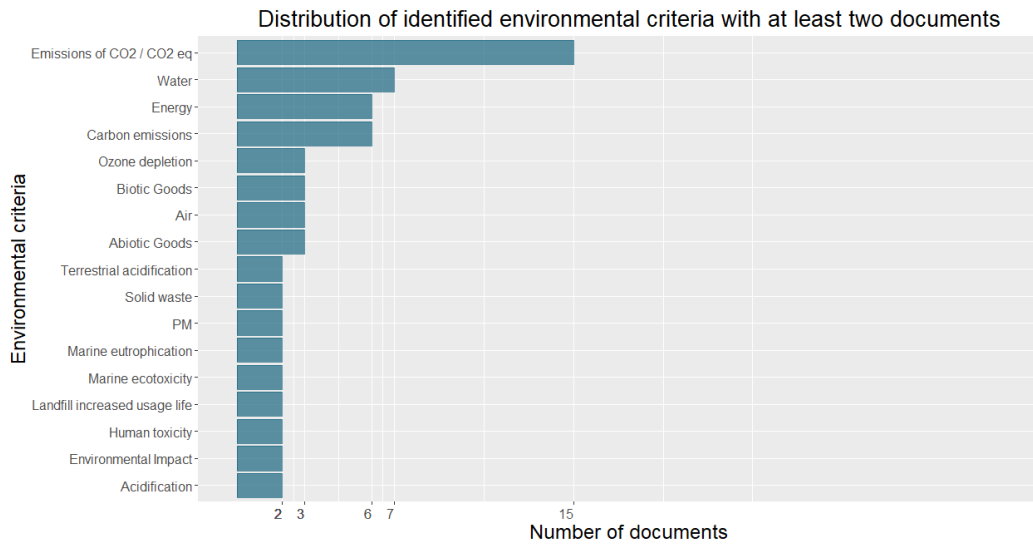


Figure I.12. Distribution of identified environmental criteria with at least two documents

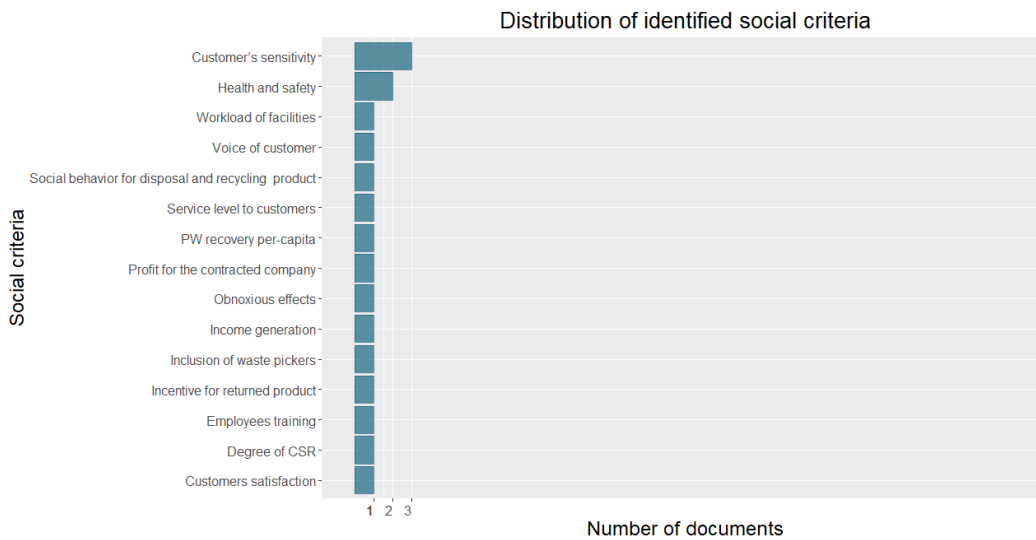


Figure I.13. Distribution of identified social criteria

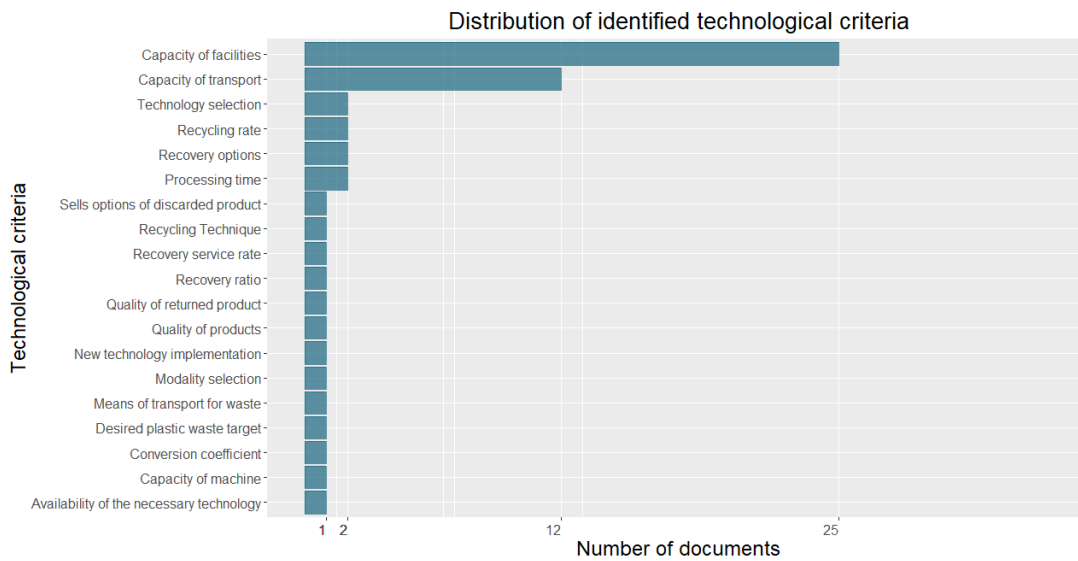


Figure I.14. Distribution of identified technological criteria

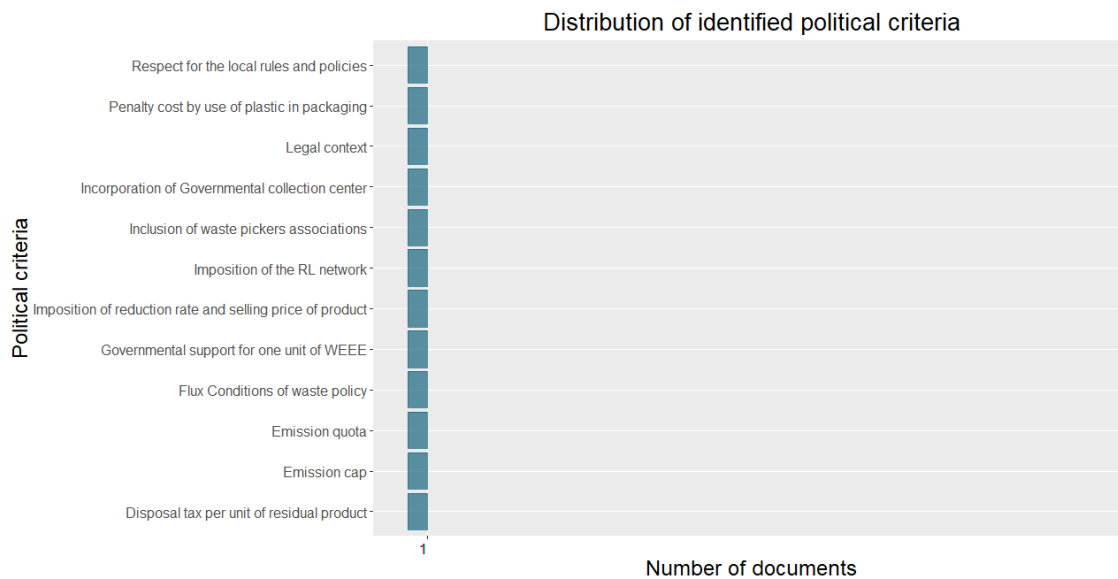


Figure I.15. Distribution of identified political criteria

1.5. Discussion

The implementation of plastic recycling networks is a key aspect to face the environmental problems derived from this material. However, at its evaluation stage, the networks to be implemented must comply with the condition of being sustainable.

In this study, a systematic analysis of the literature has been carried out in order to know how the plastic recycling networks has been studied and evaluated considering the five dimensions of sustainability.

Among the documents analyzed, approximately 28% studied a CLSC-type network. In addition, all of them presented a centralized approach to recycling in large quantities. Regarding the products considered, most of them consider plastic in general and there is an interest in the literature in the study of recycling networks for plastic bottles. This product has been studied considering CLSC and RL-RSC networks. Examples of this type of studies are [Soleimani, Seyyed-Esfahani and Shirazi \[59\]](#), [Matar, Jaber and Searcy \[56\]](#), [Sheriff, Nachiappan and Min \[57\]](#), [Papen and Amin \[52\]](#) and [Han et al. \[53\]](#) for CLSC networks of plastic bottles, and [Bloemhof-Ruwaard et al. \[80\]](#), [Kuczenski and Geyer \[97\]](#), [Sheriff et al. \[87\]](#), and [Jayanty, Sawaya III and Johnson \[81\]](#) for RL-RSC networks of plastic bottles.

From the point of view of sustainable evaluation methodologies, most of the selected articles use both mono-objective and multi-objective optimization models. On the other hand, methodologies related to environmental evaluation have frequently been considered. For example, Life cycle analysis. Considering the sustainability dimensions, most of the studies consider the economic, environmental and technological dimensions. On the other hand, the social and political dimensions correspond to those less considered. Only one study considered all five dimensions simultaneously by means of a PESTLE analysis ([Chavez & Sharma \[50\]](#)). However, it only considers the economic and environmental dimensions in a quantitative way. As a methodology used for the integration of sustainability dimensions, optimization has been identified as the most used. Regarding the criteria for each dimension, the literature presents a

large number of economic and environmental criteria to be considered, determined by costs (for the economic dimension) and CO₂ emissions or life cycle analysis criteria (for the environmental dimension). On the other hand, compared to the environmental and economical dimensions, the literature on plastic recycling networks does not present a large number of criteria for the political, social and technological dimensions (12, 15 and 19 criteria respectively). However, it should be noted that, for the technological dimension, aspects related to the capacity of the facilities and the capacity of the means of transport are frequently considered (25 and 12 documents respectively) (e.g, Darbari, Agarwal and Jha [71], Gholizadeh, Tajdin and Javadian [58], Sheriff et al [87], Kuvvetli and Erol [65]). For the social dimension, the consumer's sensitivity corresponds to the most frequent aspect ([55], [63], [64]). Finally, for the political dimension, it has been possible to identify different aspects such as, taxes [82], legal context [50], government impositions [55], [78] and penalties [51].

New models and approaches to plastic recycling networks are needed today to address the environmental problems of this material. This research presents an overview of the models and structures of plastic recycling networks studied in the literature. In addition, it presents how these networks have been evaluated from the point of view of sustainability. This research serves as a basis for exploring new models or approaches to plastics recycling in order to support the environmental challenges around this material. Also, this research presents aspects to be considered in the evaluation of future plastic recycling networks from the sustainability point of view.

1.6. Summary

In this chapter, a systematic literature review has been conducted in order to understand the way in which plastic recycling networks have been studied considering the five dimensions of sustainability. A total of 57 journal articles and conference papers have been selected and analyzed.

From the recycling network structure point of view, despite the existence of a large number of articles related to the evaluation of plastic recycling networks, both for CLSC and RL-RSC, these only explore the centralized plastic recycling approach. Therefore, the distributed plastic recycling approach has not been explored. This emerging plastic recycling approach could be addressed through optimization models, which, according to the results, corresponds to the most widely used methodology in the literature of plastic recycling networks evaluation.

Considering the sustainability dimensions, this research serves as a basis for the sustainability evaluation of new models or approaches to plastics recycling. However, it is still necessary to explore how to consider the social, technological and political dimensions, which correspond to the less considered dimensions in the context of plastic recycling networks.

The next chapter explores, in within the context of recycling networks in general, how these last three dimensions (social, technological and political) have been considered in the literature.

Chapter II. Social, political and Technological dimensions for the sustainability evaluation of recycling networks. A literature review

2.1. Chapter introduction

The results of the analysis carried out in [Chapter II](#) have shown that the social, political and technological dimensions of sustainability have been little considered in the context of reverse supply chains (or reverse logistics) and closed-loop supply chains of plastic recycling and, therefore, there were no clear indicators for their evaluation. Considering this aspect, only three articles have been found related to sustainability indicators for CLSC or RL-RSC networks. [Fernandes et al. \[107\]](#) carried out an analysis of literature on performance indicators for RL in the context of a company. Their analysis identified indicators related to economic, consumer, internal operations, learning and growth, social, environmental and supplier aspect. On the other hand, [Malladi and Sowlati \[108\]](#) carried out a literature review on sustainable inventory routing models in the context of CLSC and RL networks. They identified the way in which the economic, environmental and social objectives are considered in this type of problems. Finally, [Moreno-Camacho et al. \[109\]](#) conducted a literature analysis on the way in which economic, social and environmental aspects are considered in supply chain network design problems. In the analysis they considered networks type Forward Supply Chains, Reverse Supply Chains and Closed-loop Supply Chains. However, these works are not specifically oriented to recycling networks nor do they consider the political and technological dimensions. Therefore, the question of how a recycling network should be evaluated considering the five dimensions of sustainability, remains open. This question could be answered by considering sustainability assessments in the context of forward supply chains. However, literature reviews highlight (1) the little consideration of social, technological and political aspects in sustainability assessments, and (2) the great consideration of economic and environmental aspects [48], [109], [110] On the one hand, economic and environmental aspects are generally represented by costs and air pollution, which can be applied to the recycling network context [109]. On the other hand, how to consider social, technological and political aspects in a recycling network is not yet clear. In order to tackle this issue, this chapter seeks to provide answers to the following research question: How should be considered the social, technological and political aspects in the evaluation of a sustainable recycling network? This chapter aims to address this research gap by means of a bibliographic analysis of a set of articles about recycling networks with sustainability orientation. Again, the bibliographic analysis is carried out through a systematic literature review.

2.2. Methodology and data selection

In this research, a systematic literature review approach is carried out based on the guidelines of [Siddaway et al. \[49\]](#). [Table II.1](#) details the steps followed for the article selection. Then, a systematic selection of the literature has been carried out. The procedure of articles selection is shown in [Fig. II.1](#).

Table II.1. Systematic review protocol for the literature

Stage	Principle	Description
Search Strategy	Type of studies	Journals papers
	Keywords	Closed-loop supply chains, Reverse Logistics OR Reverse supply chains, Recycling, Sustainable, Political dimension, Technological dimension, Social dimension
	Search equation	("Closed-loop supply chain*" OR "Closed loop supply chain*" OR "Reverse Logistic*" OR "Reverse supply chain*") AND (recycl*) AND (sustainab*) AND (social* OR (politic* OR polic*) OR technolog*)
	Period of time	Until October 2019
	Databases	Scopus, Springer and Web of Science
Study Selection	Criteria	1) Articles related to the analysis or evaluation of recycling networks (for selection by abstract). 2) Articles that consider the social, technological or political dimensions of sustainability (for selection by reading).
	Procedure	1) Title, abstract and keywords are screened 2) Full article was reviewed 3) Selection is made based on selection criteria
Data extraction	Social, Political and Technological dimensions	Methodology, criteria and indicators considered for each dimension

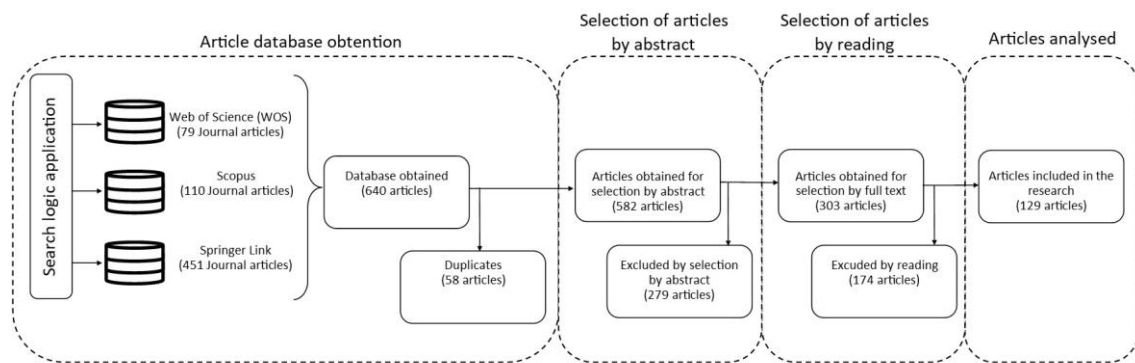


Figure II.1. Systematic article selection

From the search in the different databases, a total of 640 studies written in English were identified. Among the studies identified, 58 correspond to duplicate studies, leaving a total of 582 articles to be selected. Then, a selection by abstract was carried out, leaving only those articles related to the analysis or evaluation of recycling networks. Only 303 articles passed this filter. Finally, a selection by reading was carried out, selecting only those articles that consider at least one of the three dimensions of sustainability studied. As result, 129 articles were selected for this research.

2.3. Results

Table II.2 presents the detailed description of the set of 129 studies considered in this review. The following sections present the results obtained. First, a quantitative analysis of the selected articles and the identified criteria is presented. Then, a qualitative analysis is presented, where the way in which each identified criterion has been considered in the literature is described.

Table II.2. Analysis of the 129 publications selected in this study

Article	Dimensions	Method	Product / Application	Year
[111]	Soc+Tech+Po	Discounted cash flow	Municipal solid waste	2017
[112]	Soc+Tech+Po	Game theory	E-waste	2019
[113]	Soc+Tech+Po	Game theory	General	2019
[114]	Soc+Tech+Po	Game theory	General	2019
[115]	Soc+Tech+Po	Interpretive Structural Modeling (ISM)	Paper	2012
[116]	Soc+Tech+Po	Multi-Criteria and Optimization	E-waste	2019
[117]	Soc+Tech+Po	Multi-Criteria and Optimization	E-waste	2019
[118]	Soc+Tech+Po	Multi-Criteria decision making	E-waste	2016
[119]	Soc+Tech+Po	Optimization	E-waste	2018
[120]	Soc+Tech+Po	Optimization	General	2019
[121]	Soc+Tech+Po	Optimization	Medical waste	2019
[68]	Soc+Tech+Po	Optimization	Municipal solid waste	2015
[122]	Soc+Tech+Po	Optimization	Perishable products	2016
[50]	Soc+Tech+Po	PESTLE analysis	Plastic	2018
[123]	Soc+Tech+Po	Qualitative analysis	Photovoltaic technologies	2019
[124]	Soc+Tech+Po	System Dynamics	E-waste	2008
[125]	Soc+Tech+Po	System Dynamics	E-waste	2010
[126]	Soc+Tech+Po	System Dynamics	E-waste	2012
[127]	Soc+Tech+Po	System Dynamics	E-waste	2017
[128]	Soc+Tech+Po	Variational inequality	General	2018
[66]	Soc+Tech	Discrete event simulation (DES)	Municipal solid waste	2019
[129]	Soc+Tech	Game theory	General	2019
[130]	Soc+Tech	Game theory	General	2019
[131]	Soc+Tech	Multi-Criteria and Optimization	Bicycles	2019
[132]	Soc+Tech	Multi-Criteria decision making	End of life vehicles	2013
[133]	Soc+Tech	Multi-Criteria decision making	End of life vehicles	2016
[134]	Soc+Tech	Multi-Criteria decision making	End of life vehicles	2016
[135]	Soc+Tech	Multi-Criteria decision making	E-waste	2016
[136]	Soc+Tech	Multi-Criteria decision making	Light bulbs	2018
[137]	Soc+Tech	Multi-Criteria decision making	Municipal solid waste	2019
[138]	Soc+Tech	Optimization	Construction and demolition wastes	2018
[139]	Soc+Tech	Optimization	E-waste	2013
[140]	Soc+Tech	Optimization	E-waste	2014
[141]	Soc+Tech	Optimization	E-waste	2017
[142]	Soc+Tech	Optimization	E-waste	2017
[143]	Soc+Tech	Optimization	General	2017
[144]	Soc+Tech	Optimization	General	2018
[145]	Soc+Tech	Optimization	General	2019
[146]	Soc+Tech	Optimization	General	2019
[147]	Soc+Tech	Optimization	Glass	2019
[148]	Soc+Tech	Optimization	Hazardous waste	2018
[149]	Soc+Tech	Optimization	Kitchenware	2019
[150]	Soc+Tech	Optimization	Light bulbs	2019
[151]	Soc+Tech	Optimization	Magnets	2018
[152]	Soc+Tech	Optimization	Medical waste	2016
[153]	Soc+Tech	Optimization	Municipal solid waste	2018
[46]	Soc+Tech	Optimization	Tire	2018
[67]	Soc+Tech	Optimization and LCA	Plastic	2017
[11]	Soc+Tech	System Dynamics	Gold from cellphones	2018
[154]	Soc+Po	Game theory	General	2018
[155]	Soc+Po	Game theory	General	2019
[55]	Soc+Po	Game theory	General	2019

Table II.2. Analysis of the 129 publications selected in this study (Continuation)

Article	Dimensions	Method	Product / Application	Year
[156]	Soc+Po	Multi-Criteria and Optimization	E-waste	2016
[74]	Soc+Po	Multi-Criteria and Optimization	Plastic	2017
[157]	Soc+Po	Qualitative analysis	Tire	2018
[158]	Soc+Po	Statistical analysis	E-waste	2019
[159]	Soc	Case study analysis	General	2014
[160]	Soc	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	2016
[75]	Soc	Financial analysis	E-waste	2018
[161]	Soc	Game theory	Batteries	2019
[162]	Soc	Game theory	E-waste	2017
[163]	Soc	Game theory	General	2019
[164]	Soc	Game theory	General	2019
[63]	Soc	Game theory	Plastic, glass and metal	2019
[77]	Soc	Hybrid BSC-DEA (balanced scorecard - data envelopment analysis)	Plastic	2016
[165]	Soc	Multi-Criteria decision making	E-waste	2016
[166]	Soc	Multi-Criteria decision making	General	2019
[167]	Soc	Optimization	Biomass	2017
[168]	Soc	Qualitative analysis	General	2010
[169]	Soc	Scenario analysis and quantification	Biorefinery	2018
[170]	Soc	Statistical analysis	General	2013
[171]	Soc	Statistical analysis	General	2014
[172]	Tech+Po	Action research	E-waste	2018
[173]	Tech+Po	Game theory	Cooking oil	2019
[174]	Tech+Po	Game theory	General	2019
[83]	Tech+Po	Optimization	E-waste	2015
[175]	Tech+Po	Optimization	General	2014
[176]	Tech+Po	Optimization	General	2017
[51]	Tech+Po	Optimization	General	2018
[177]	Tech+Po	Optimization	General	2019
[178]	Tech+Po	Optimization	Metal	2013
[179]	Tech+Po	Optimization	Tire	2018
[180]	Tech+Po	Quality-based price competition model	E-waste	2016
[181]	Tech+Po	Surveys Analysis	General	2015
[182]	Tech	Game theory	E-waste	2018
[183]	Tech	Grey prediction model and Optimization	Medical waste	2019
[184]	Tech	Multi-Criteria decision making	E-waste	2011
[185]	Tech	Optimization	Apparel	2017
[186]	Tech	Optimization	Automotive industry	2015
[187]	Tech	Optimization	Batteries	2015
[188]	Tech	Optimization	Building waste	2018
[69]	Tech	Optimization	Carbon fibre reinforced polymers (CFRP)	2017
[189]	Tech	Optimization	End of life vehicles	2006
[190]	Tech	Optimization	End of life vehicles	2017
[191]	Tech	Optimization	E-waste	2015
[192]	Tech	Optimization	E-waste	2016
[58]	Tech	Optimization	E-waste	2018
[193]	Tech	Optimization	E-waste	2018
[194]	Tech	Optimization	Food industry	2019
[195]	Tech	Optimization	General	2010
[196]	Tech	Optimization	General	2012
[197]	Tech	Optimization	General	2014
[198]	Tech	Optimization	General	2014
[199]	Tech	Optimization	General	2016
[200]	Tech	Optimization	General	2016
[201]	Tech	Optimization	General	2017
[202]	Tech	Optimization	General	2017
[203]	Tech	Optimization	General	2018
[204]	Tech	Optimization	General	2018
[205]	Tech	Optimization	General	2019
[206]	Tech	Optimization	Household waste	2019
[207]	Tech	Optimization	Municipal solid waste	2017
[208]	Tech	Optimization	Photovoltaic technologies	2014
[10]	Tech	Optimization	Plastic	2014

Table II.2. Analysis of the 129 publications selected in this study (Continuation)

Article	Dimensions	Method	Product / Application	Year
[53]	Tech	Optimization	Plastic bottles	2017
[52]	Tech	Optimization	Plastic bottles	2019
[60]	Tech	Optimization	Plastic pallets	2018
[209]	Tech	Optimization	Post-consumer packages	2017
[210]	Tech	Optimization	Solar energy industry	2017
[211]	Tech	Optimization	Vegetable oil	2012
[212]	Tech	Statistical analysis	Steel	2018
[213]	Tech	System Dynamics	End of life vehicles	2018
[78]	Po	Cost analysis	E-waste	2017
[214]	Po	Game theory	Photovoltaic technologies	2019
[79]	Po	Optimization	Plastic	2015
[215]	Po	Optimization	Rare metals	2018
[216]	Po	Qualitative analysis	E-waste	2010
[217]	Po	System Dynamics and grey model theory	Construction and demolition wastes	2018
[218]	Po	Theoretical model	E-waste	2009

2.3.1. Quantitative Analysis

Figure II.2 shows the ranking of journals with at least three documents considered in this review being Journal of Cleaner Production the most representative among the database. From the point of view of the profile of journals, it is possible to observe journals oriented to environmental aspects and sustainable development. For example, Journal of cleaner production, Waste management, Sustainability, and Resources, Conservation, and recycling. On the other hand, it is also possible to observe journals with an operational or manufacturing profile. For example, International Journal of Advanced Manufacturing Technology, Annals of Operations Research, Journal of Remanufacturing, Operational Research. Figure II.3 shows the temporal distribution of the articles considering the dimensions studied in this research. Figure II.3 confirms a growing interest in the subject since 2016 for each sustainable dimension. Comparing the three dimensions, the technological dimension has been the most considered. On the other hand, the political dimension has been the least considered. Figure II.4 shows the temporal distribution of the dimensions studied considering their integration. Figure II.4 shows the growing interest in recent years in considering the technological dimension and the integration of the social and technological dimensions. An increase in the integration of the three dimensions (social, political and technological) can also be observed. Finally, Figure II.5 shows the distribution of the identified criteria considering their dimension, type of indicator (if it was measured qualitatively or quantitatively) and the methodology used. As can be observed in Figure II.5, the criteria associated with the social dimension have been measured using both qualitative and quantitative indicators in almost equal numbers. On the other hand, most of the criteria associated with the technological and political dimensions have been measured using quantitative indicators. From the methodological point of view, the criteria associated to quantitative indicators have been integrated using optimization, game theory or dynamic systems. On the other hand, most of the criteria associated to qualitative indicators have been integrated by means of multi-criteria methods.

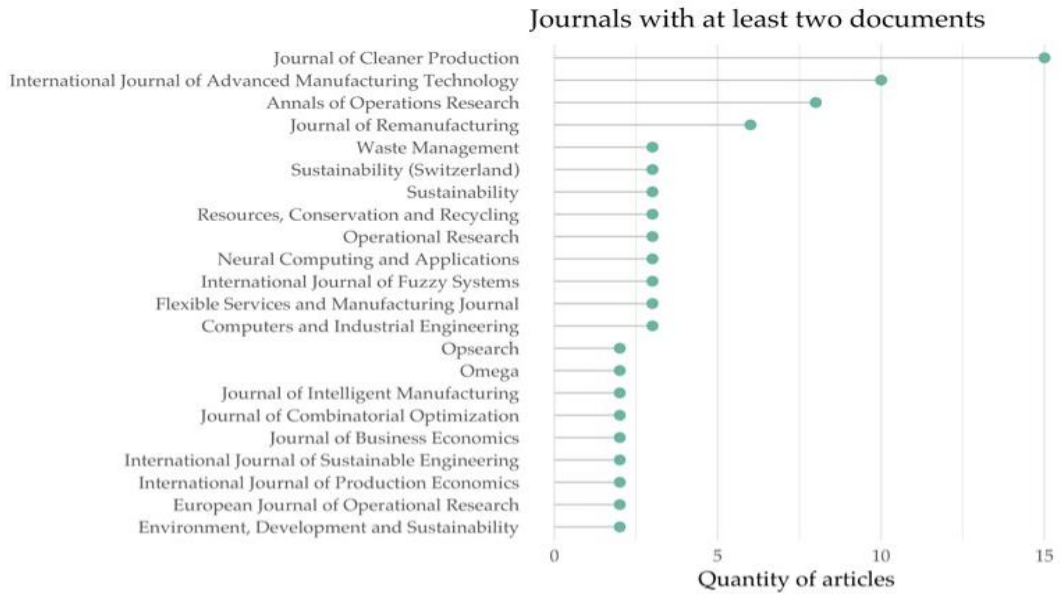


Figure II.2. Descriptive analysis of selected article

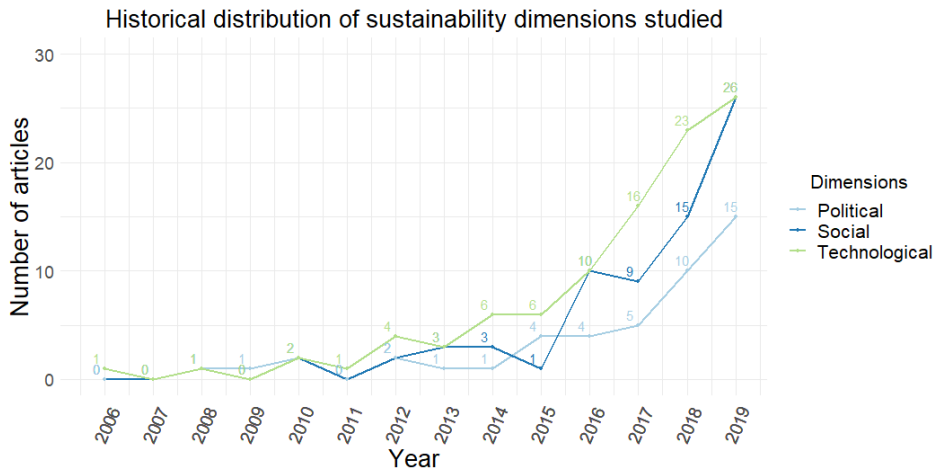


Figure II.3. Historical integration of dimensions

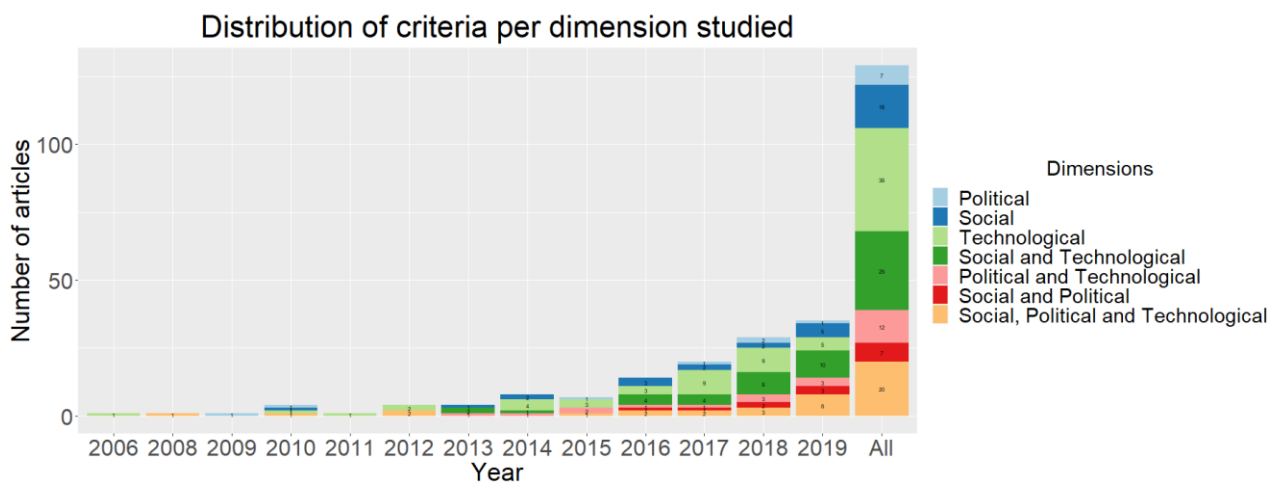


Figure II.4. Historical distribution of integrated dimensions

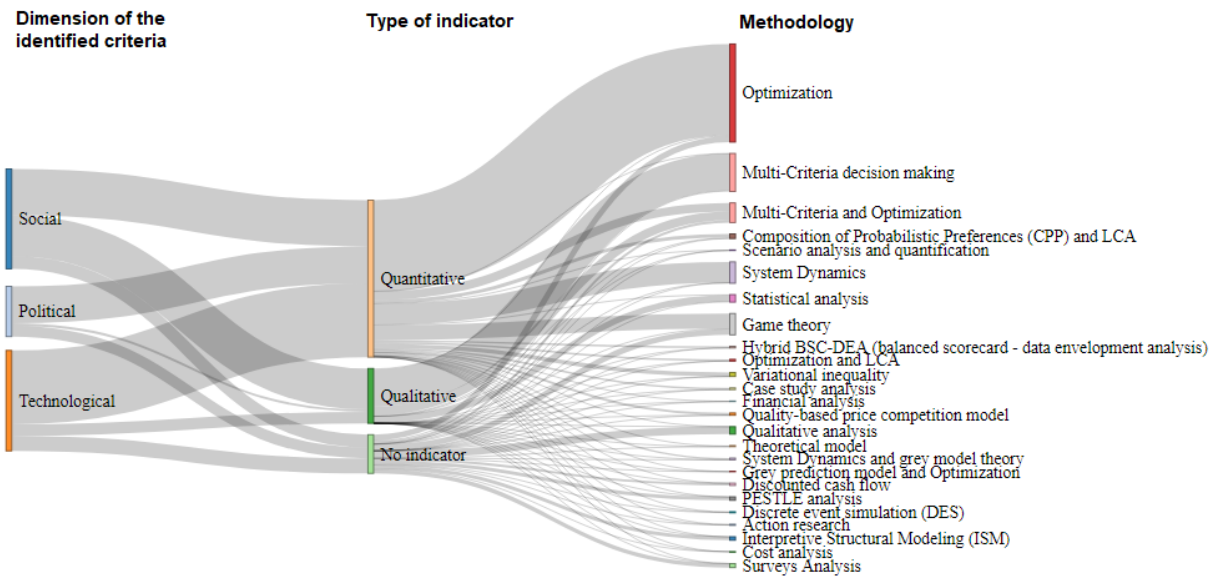


Figure II.5. Distribution of criteria, indicators and methodologies

2.3.2. Qualitative Analysis

The following subsections present a detailed qualitative analysis of how sustainability-oriented recycling network consider social, political and technological dimensions. First, the analysis of the social dimension is presented in [section 2.3.2.1](#). Then, the analysis of the political dimension is presented in [section 2.3.2.2](#). Technological dimension is presented in [section 2.3.2.3](#). Finally, a global analysis is presented in [section 2.3.2.4](#).

2.3.2.1 Social Dimension

Considering the social dimension, a total of 78 criteria were identified in 72 of the 129 documents selected literature. For a better understanding, the criteria identified for the social dimension were divided in four types of perspectives regarding the concerned stakeholder to which each criterion was oriented: 1) to the worker, 2) to the consumer, 3) to the community and 4) to company. As a workers' perspective, we have identified those criteria that consider the impact on workers due to recycling activity. As a consumers' perspective, we have identified those criteria that consider the impact of the recycled product on the consumer or their preference. As community perspective, we have identified those criteria that consider the impact of the recycling activity on the community. As company perspective, we have identified those criteria that consider the impact of the recycling activity on the social performance/image of the company. Finally, a fifth category was made to group certain social factors that are not classified in some of the perspectives already mentioned. [Figure II.6](#) presents the distribution of the criteria in each defined group. [Figure II.7](#) shows the presentation structure considering each group.



Figure II.6. Distribution of social criteria by number of occurrences

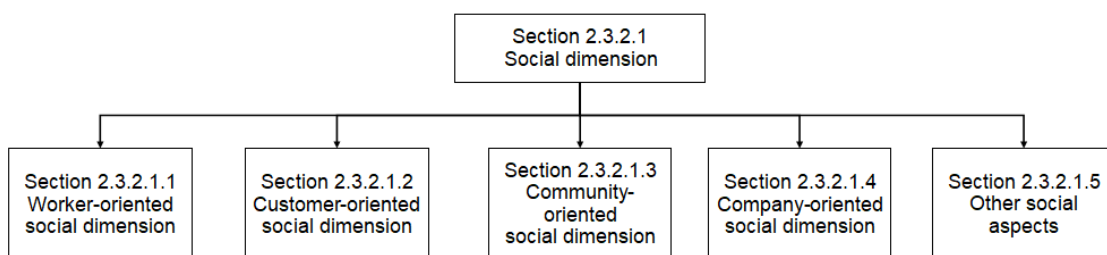


Figure II.7. Structure of social dimension section

2.3.2.1.1 Worker-oriented

As can be observed in [Figure II.6](#), a total of 18 worker-oriented social criteria were identified. [Appendix II.1](#) details the criteria, indicators and the methodology in which the criterion was used. [Figure II.6](#) shows that **Job creation or employment** is one of the most widely used worker-oriented social criteria in the literature analyzed (21 documents). The job creation criterion

refers to the number of jobs created or number of employees by the implementation of a recycling network. This criterion has been used mainly for the design and planning of recycling networks by means of optimization models (e.g. Taleizadeh et al. [150]; Sahebjamnia et al. [46]), who have considered this criterion as the number of created jobs opening facilities. **Safety of workers** and **Health of workers** correspond to the second and third most used worker-oriented social criteria in the selected literature (10 and 8 documents respectively). **Safety and Health of workers** refers to health and safety during operations in the recycling network. These criteria have been considered quantitatively (lost days) for the design and planning of recycled network using optimization models (e.g. Taleizadeh et al. [150]) and qualitatively in multi-criteria methods for third-party reverse logistics providers (3PRLP) selection (e.g. Mavi et al. [74]) or recovery selection (e.g. Ahmed, Ahmed, Md Rezaul Hasan Shumon et al. [134]). **Damage to workers** corresponds to the fourth more considered worker-oriented criteria (7 documents). This criterion is associated with damage due to the handling of hazardous waste in the stages of recycling or by the installation of facilities. Quantitatively, it has been represented as a score or lost days in the design of recycling network using optimization models (e.g. Sahebjamnia et al. [46]; Rahimi and Ghezavati [138]). The fifth and sixth criteria corresponds to **Employment stability** (5 documents) and **Employment practices** (5 documents). **Employment stability** take into account variations in the number of employees of the recycling network, mainly due to the uncertainty in which these networks are involved with respect to the collection of waste or discarded products. This criterion has been considered in the literature in a qualitative way in the analysis of recycling networks or in multi-criteria methods to third-party reverse logistics provider (3PRLP) selection (e.g. Mavi et al. [74]; Agrawal et al. [165]). **Employment practices** represents qualitatively the effects on workers in terms of disciplinary and security practices, employee contracts, equity labor sources, job creation, job satisfaction, wages, employee training, etc. (e.g. Ahmed et al. [134]; Govindan et al. [117]). Finally, it has been possible to identify in the literature twelve less used worker-oriented social criteria: **Job satisfaction** [150], **Employee benefits** [158], [165], **Working hours** [140], **Access to healthcare** and **Access to education** [160], **Labor equity and supplier stock management** and **Flexible working arrangements** [74], **Human capital** [168], **Training and education to employees** and **Establishment of new employment opportunities** [116], **Total employee fund generated** [156] and **Workers status** [111].

2.3.2.1.2 Customer-oriented

Considering the consumer-oriented social criteria, Figure II.6 shows that total of 13 consumer-oriented social criteria were identified. Appendix II.2 details the criteria, indicators and the methodology in which the criterion was used. As can be observed in Figure II.6, **Health of consumer**, **Safety of consumer**, **Consumer preference**, **Sensitivity of the customers** and **Incentives to customers** are the most used consumer-oriented criteria found (4 documents for each one). **Health of consumer** and **Safety of consumer** refer to the safety and health due to the use of products obtained from the recycling of waste. These criteria have been used qualitatively in multi-criteria methods to evaluate RL networks (e.g. Agrawal et al. [165]; Agrawal et al. [118]) and quantitatively in optimization model for network design (e.g. Taleizadeh et al. [150]). **Consumer preference** has been considered as the preference for recycled products or green product [114], [154], [155]. Another form of consumer preference was considered in the work of Niranjana et al. [149], which considers consumers' preference for online or offline sales

channels in a CLSC. **Sensitivity of the customers** represents the consumers' preference for a product considering its characteristics (if the product is manufactured from recycled or non-recycled material, or the level of quality and sustainability) [55], [112]. Similarly, manufacturer's characteristics can affect consumer's sensitivity (e.g. level of green innovation) [129], [130]. **Incentives to customers** refers to monetary incentives to consumers in order to motivate the return of discarded products for proper treatment (e.g. Fattahi and Govindan [143]; Allevi et al. [128]). Finally, it has been possible to identify in the literature eight less used consumer-oriented social criteria: **Voice of customer** [74], **Firm's service quality** [170], **Service level** [67], **Consumer behavior for disposal and recycling product** [50], [157], [158], **Product harming the customers** [144], **Accessibility and responsiveness to customers** [145], **Participation rate**, [167] and **Public engagement** [123].

2.3.2.1.3 Community-oriented

As community-oriented social criteria, Figure II.6 shows that 23 criteria have been identified in this group. Appendix II.3 details the criteria, indicators and the methodology in which the criterion was used. As can be observed in Figure II.6, **Donation to community** corresponds to the most frequent criterion in this group (4 documents). It refers to the monetary donation for social work. This criterion has been considered quantitatively as amount donated (e.g. Modak et al. [163]), and qualitatively measured using multi-criteria methods for performance evaluation (e.g. Agrawal et al. [165]). **Corporate social responsibility** and **Inclusion of waste pickers** correspond to the second most used criteria in this group (3 documents). On the one hand, **Corporate social responsibility** refers to the company's commitment to social impacts [63], [135], [161]. On the other hand, **Inclusion of waste pickers** refers to the inclusion of non-formal collectors in a recycling network. This aspect has been considered quantitatively by Ghisolfi et al., [127] as a ratio of formalization of non-formal collectors in a CLSC of desktops and laptops. On the other hand, Ferri et al. [68] and Pongeluppe Wadhy Rebehy et al. [111] studied a network based on the integration of waste pickers for municipal solid waste. **Local community influence**, **Social cost of carbon**, **Local development** and **Community complaints** correspond to the third most considered criteria in this group (2 documents). **Local community influence** considers cultural support and activities in the community [117], [136]. **Social cost of carbon** represents to monetarily the social benefits/impacts for the implementation of the network [153], [179]. **Local development** refers to the development of the community by the installation of network facilities [139], [141]. **Community complaints** refers to the number of complaints resolved for performance evaluation of RL networks [158], [165]. Finally, it has been possible to identify sixteen less used community-oriented social criteria: **Ecological risk and safety risk** [134], **Disturbance in Public Places** [137], **Social cost based on disposal** [121], **Social inclusion** [160], **Respect for local rules and policies** [74], **Communities influence** [118], **Reduction of vehicle accident rate** and **Vehicle noise emission** [122], **Community capital** [168], **Level of social support** [151], **Effect of production on self-sufficiency** [150], **Community service** and **Products donated to NGOs** [116], **Waste recycled** [162] and **Risk of transport and installation of facilities** [148].

2.3.2.1.4 Company-oriented

As company-oriented social criteria, [Figure II.6](#) shows that 5 criteria have been identified in this group. [Appendix II.4](#) details the criteria, indicators and the methodology in which the criterion was used. As can be observed in [Figure II.6](#), **Green Image** and **Customer satisfaction** are the most used criteria in this group (5 documents). On the one hand, **Green image** is related to the image of the company towards consumers or society, considering that the company carries out recycling activities. This factor has been considered quantitatively in system dynamics for CLSC networks [\[124\]](#), [\[125\]](#), and qualitatively in 3PRLP selection using MCDM methods [\[136\]](#). On the other hand, **Customer satisfaction** refers to the conformity of consumers with respect to the product or service provided by the company [\[115\]](#), [\[120\]](#), [\[134\]](#), [\[166\]](#). This factor has been used mainly in a qualitative way in multi-criteria methods [\[134\]](#), [\[166\]](#). **Corporate Image** corresponds to the second most used criteria in this group (4 documents). **Corporate Image** considers the reputation of the company to the public after the implementation of the network. This criterion had been measured qualitatively in literature using MCDM methods [\[118\]](#), [\[133\]](#), [\[134\]](#). Finally, it has been possible to identify in the literature other less used company-oriented social criteria. **Income generation for collectors or contracted company**, which represents generation of monetary incomes by the new actors integrated in the recycling network [\[66\]](#), [\[75\]](#), [\[160\]](#). And, **Stakeholders participation**, which refers to the stakeholders' engagement with the network [\[158\]](#), [\[165\]](#).

2.3.2.1.5 Other social aspects

Finally, a total of 17 identified social criteria have not been classified into any of the four groups above (worker, consumer, community, or company oriented) (see [Figure II.6](#)). [Appendix II.5](#) details the criteria, indicators and the methodology in which the criterion was used. As can be observed in [Figure II.6](#), the criteria associated with this group have not been widely considered in the selected literature (they have only been considered in one article). The identified criteria are the following: **Safety of road**, **Health of road**, **Distribution Services** and **Access to markets** for recovery option selection [\[137\]](#). **Amount of expired products** for sustainable inventory routing problems [\[122\]](#). **Market demand** for recovery selection [\[135\]](#). **Productive capital**, which refers to the places of collection available [\[168\]](#). **Contractual stakeholders influence** and **Reputation** 3PRL provider selection [\[136\]](#). **Percent recycling** and **Product green efficiency** for performance evaluation of RL [\[159\]](#). **Effective communication**, **Service improvement** and **Overall working relations** for 3PRL provider selection [\[132\]](#). **Public acceptability** for sustainable management alternatives selection [\[133\]](#). Finally, **Market edge** and **Customer redundancy** for a product recovery system [\[115\]](#).

In conclusion, considering the number of articles in which the criterion has been considered, job creation corresponds to the most used among all the groups. However, as observed in the analysis, the social dimension has been considered in the literature from different perspectives. Therefore, in order to make a more holistic analysis, the social dimension should be considered from more than one perspective. Considering each perspective separately, elements such as job creation and, worker health and safety, are the most considered from the worker-oriented perspective. From the community perspective, the impact of the network on community development and social inclusion are the most considered. From the consumer's perspective,

their preference and their health and safety are the elements most considered. Finally, from the company's perspective, the impact on its image is an element frequently considered.

2.3.2.2 Political Dimension

Considering the political dimension, a total of 29 criteria were identified in 46 of the 129 documents selected literature. For a better understanding, the identified political criteria were divided into four groups: 1) incentive/punishment-oriented policies, 2) Active government policies, 3) Emission policies and 4) Legal policies. As Incentive/punishment-oriented policies we have identified those policies of punishment or incentives that are directly focused on recycling. As active government policies we have identified those policies in which the government actively participates. As emission policies, we have identified those policies related to the emissions generated by the recycling activity. As legal policies, we identified the legal context regarding the recycling activity. Finally, a fifth category was made to group certain political factors that are not classified in some of the groups mentioned. Figure II.8 presents the distribution of the criteria in each defined group. Figure II.9 shows the presentation structure considering each group.

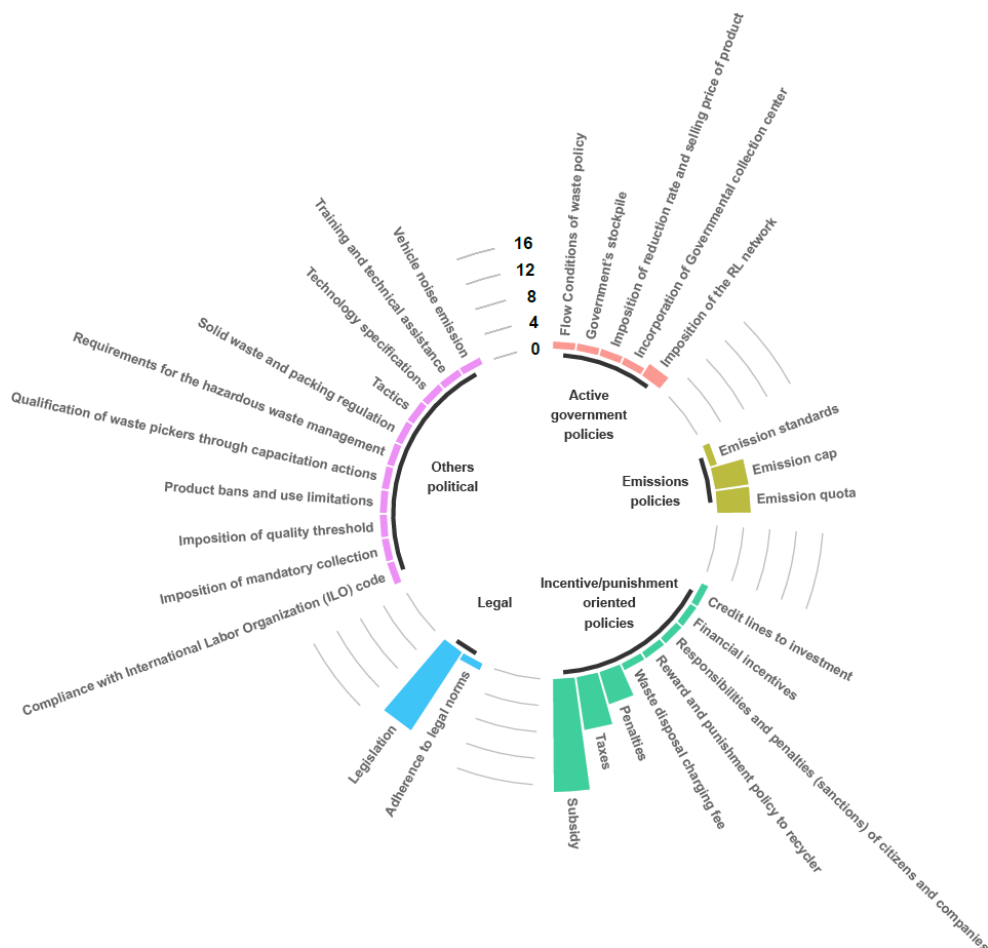


Figure II.8. Distribution of political criteria by number of occurrences

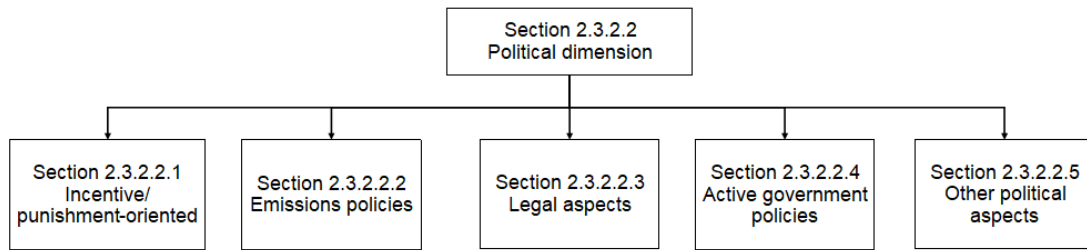


Figure II.9. Structure of political dimension section

2.3.2.2.1 Incentive/punishment-oriented policies

As can be observed in [Figure II.8](#), a total of 8 criteria were identified as incentive/punishment-oriented policies. [Appendix II.6](#) details the criteria, indicators and the methodology in which the criterion was used. [Figure II.8](#) shows that **Subsidy** is one of the most considered political aspects of this group (17 documents). The subsidy has been considered in four main ways: Subsidy to the investment (e.g [Saha et al. \[113\]](#)), subsidy by product (e.g [Duan et al. \[155\]](#)), subsidy to consumer (e.g [Saha et al. \[113\]](#)) and subsidy for training employees (e.g [Darbari et al. \[116\]](#)). **Taxes** correspond to the second most considered criterion of this group (8 documents). **Taxes** criterion has been considered in different ways. For example, [Darbari et al. \[116\]](#) considered a tax credit from donation of returns. [Ghalekhondabi and Ardjmand \[112\]](#) considered a recovery tax. [Nambu and Murakami-Suzuki \[218\]](#) considered a tax for new products. [Allevi et al. \[128\]](#) and [Gao and Ryan \[175\]](#) considered a tax per carbon emission. [Besiou et al. \[126\]](#) considered a tax associated with each legislation (legislative collection percentage, scavengers' uncontrollable disposal and legislative recycling percentage). **Penalties** corresponds to the third most considered political aspect of this group (5 documents). **Penalties** represents additional costs due to regulations. For example, [Georgiadis and Besiou \[125\]](#) considered a cost per unit due to non-compliance with regulations. [Ghalekhondabi and Ardjmand \[112\]](#) considered a cost due to emissions. [Porkar et al. \[51\]](#) considered a penalty cost for the use of paper and plastic in packaging. [Jia et al. \[217\]](#) considered a penalty for illegally dumped waste. [Nidhi and Pillai \[121\]](#) considered a penalty for non-recyclable product disposed as landfill. Finally, it has been possible to identify in the literature other less used Incentive/punishment-oriented political criteria: **Reward and punishment policy to recycler [174]**, **Waste disposal charging fee [217]**, **Credit lines to investment** and **Financial incentives ([127])** and **Responsibilities and penalties (sanctions) of citizens and companies [181]**.

2.3.2.2.2 Emission policies

As emissions policies, [Figure II.8](#) shows that three emission policies have been identified in the literature. [Appendix II.7](#) details the criteria, indicators and the methodology in which the criterion was used. In this group, **Emission quota** and **Emission cap** are the most considered policies (5 documents). On the one hand, **Emission quota** represents a way of trading the carbon emissions allowed by a company (e.g [Bing et al. \[106\]](#)). On the other hand, **Emission cap** corresponds to a limit of permitted emissions (e.g [Yu and Solvang \[176\]](#)). **Emission standards** has also been considered [\[181\]](#).

2.3.2.2.3 Legal aspects

From the legal perspective, [Figure II.8](#) shows that the **legislation** has been frequently considered in the literature (14 documents). [Appendix II.8](#) details the criteria, indicators and the methodology in which the criterion was used. This aspect can encompass the legislative environment with respect to the operation and treatment of waste [\[50\]](#), [\[111\]](#), [\[123\]](#), [\[157\]](#), [\[219\]](#), [\[220\]](#) It can also include, quantitatively, limits on waste treatment, for example: minimum recycled content [\[125\]](#), minimum recycling percentage [\[124\]](#)–[\[126\]](#), minimum collection percentage [\[124\]](#)–[\[126\]](#), minimum recyclability of product [\[124\]](#), [\[125\]](#) or minimum amount of waste to be submitted [\[173\]](#). Finally, some works have qualitatively considered this aspect by means of multi-criteria methods [\[74\]](#), [\[118\]](#), [\[165\]](#). Other legal criteria identified is **Adherence to legal norms**, which has been used in the work of [Darbari et al. \[116\]](#) to define a sustainable CLSC design.

2.3.2.2.4 Active government policies

From the point of view of government participation, [Figure II.8](#) shows that five policies related to active government participation have been identified. [Appendix II.9](#) details the criteria, indicators and the methodology in which the criterion was used. The most considered of this group is **Imposition of the RL network** (2 documents), where the government imposes or proposes a network or conditions for the network [\[68\]](#), [\[78\]](#). The imposition of **Flow conditions of waste policy** has also been considered [\[68\]](#). Another policy studied in literature is the **Government's stockpile**, where the government maintains a stock of raw materials to regulate the market [\[68\]](#). **Incorporation of Governmental collection center** and **Imposition of reduction rate and selling price of product** are other two policies studied in the work of [Rezaei and Maihami \[55\]](#).

2.3.2.2.5 Other political aspects

Finally, a total of 11 identified political criteria have not been classified into any of the four groups above (Incentive/punishment-oriented, Emissions policies, Active government policies and Legal) (see [Figure II.8](#)). [Appendix II.10](#) details the criteria, indicators and the methodology in which the criterion was used. As can be observed in [Figure II.8](#), the criteria associated with this group have not been widely considered in the selected literature (they have only been considered in one article). The criteria identified are the following: **Imposition of mandatory collection**, **Qualification of waste pickers through capacitation actions** and **Training and technical assistance** [\[127\]](#), **Imposition of quality threshold** [\[180\]](#), **Technology specifications**, **Product bans and use limitations**, **Requirements for the hazardous waste management** and **Solid waste and packing regulation** [\[181\]](#), **Tactics** [\[125\]](#), **Compliance with International Labor Organization code** [\[117\]](#) and **Vehicle noise emission** [\[122\]](#).

In conclusion, considering the number of articles in which the criterion has been considered, subsidy corresponds to the most used among all the groups. However, the political dimension has been considered in the literature mainly from the legal, emissions and incentive/punishment

perspectives. The most considered criteria correspond to aspects related to legislation, subsidies, taxes, penalties and emissions. Therefore, all of these aspects must be considered in the analysis.

2.3.2.3 Technological Dimension

Considering the technological dimension, a total of 43 criteria were identified in 99 of the 129 documents selected literature. For a better understanding, the criteria identified for technological dimension were separated into two perspectives: 1) process-oriented technological factors, and 2) other technological dimension aspects. On the one hand, Process-oriented perspective consider those criteria related to the process of material transformation. On the other hand, other technological dimension aspects group the criteria that are not classified in the process-oriented perspective. Figure II.10 presents the distribution of the criteria in each defined group. Figure II.11 shows the presentation structure considering each group.

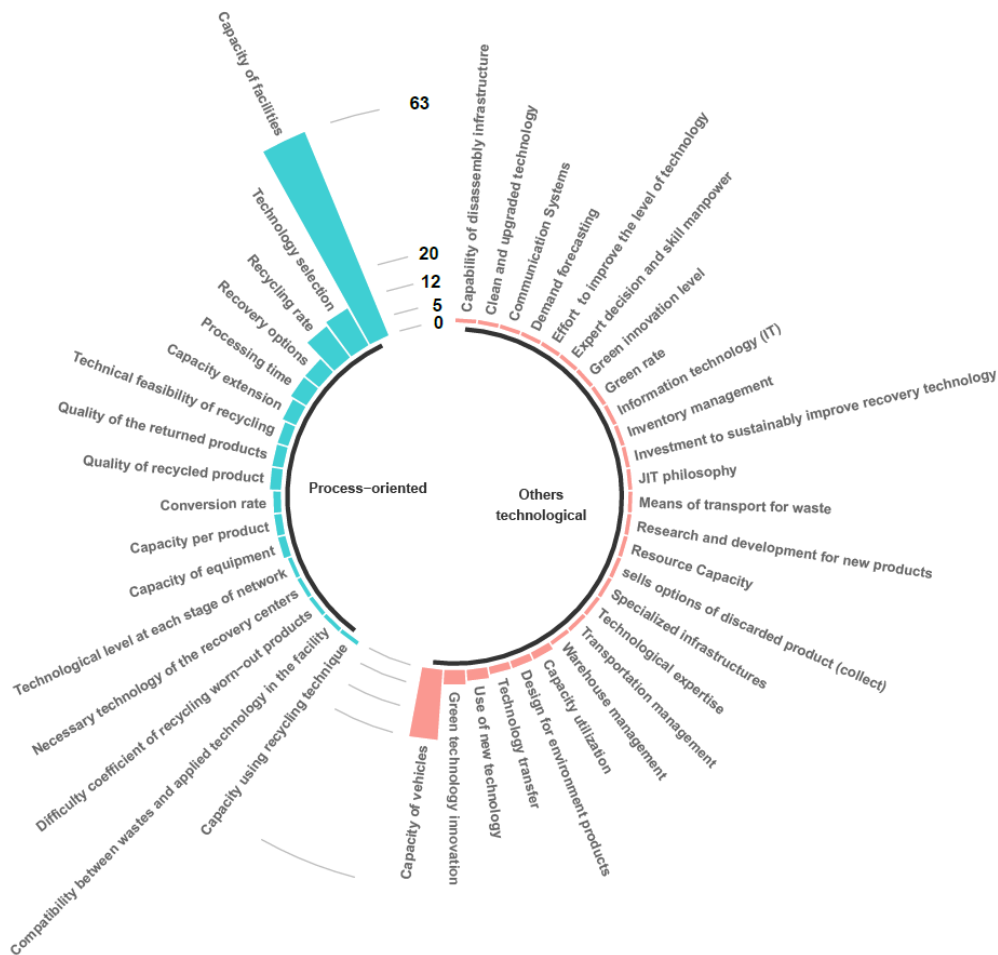


Figure II.10. Distribution of technological criteria by number of occurrences

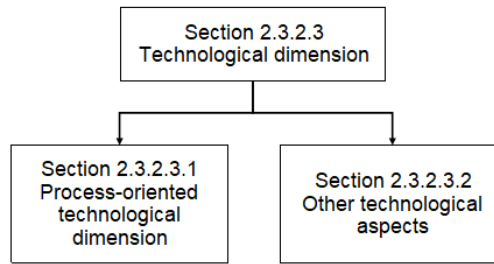


Figure II.11. Structure of technological dimension section

2.3.2.3.1 Process-oriented

As can be observed in Figure II.10, a total of 17 criteria were identified as incentive/punishment-oriented criteria. Appendix II.11 details the criteria, indicators and the methodology in which the criterion was used. Figure II.10 shows that **Capacity of facilities** has been identified as the most widely used factors in the literature (63 documents). This factor has been generally considered as a restriction in the design and planning of networks using in optimization models (e.g. Pourjavad and Mayorga [146]; Hajiaghaei-Keshteli and Fathollahi Fard [147]). **Technology selection** and **Recycling rate** correspond to the second and third most considered criteria in this group (12 and 11 documents respectively). On the one hand, **Technology selection** refers to decision decisions regarding the technology to be used in the process (e.g Chen et al. [210]). On the other hand, **Recycling rate** represents the fraction of a product that is recycled (e.g Ghisolfi et al. [127]; Besiou et al. [126]). **Recovery option** and **Processing time** correspond to the fourth most used criterion in this group (5 documents for each one). On the one hand, **Processing time** represents the time required to process a waste unit or product (Choi and Fthenakis [208]; Ghisolfi et al. [127]). On the other hand, **Recovery option** represents the decisions regarding the alternatives of recovery (incineration, recycling, remanufacturing, etc) (e.g Asees Awan and Ali [137]). Finally, it has been possible to identify in the literature other less considered process-oriented technological criteria: **Capacity of the equipment used** [187], [208], **Capacity using recycling technique** [69], **Capacity per product** [177], [209], **Capacity extension** (e.g Chen et al. [210]), **Quality of recycling** [136], [174], **Quality of the returned product or waste** (e.g Yu and Solvang [176]), **Difficulty coefficient of recycling worn-out products** [129], **Compatibility between wastes and applied technology** [148], **Technological level at each stage of network** [123], **Technical feasibility of recycling** [123], [135], [181] and **Conversion rate** [53], [199].

2.3.2.3.2 Other technological aspects

A total of 26 identified technological criteria have not been classified as process-oriented (see Figure II.10). Appendix II.12 details the criteria, indicators and the methodology in which the criterion was used. As can be observed in Figure II.10, **Capacity of vehicles** corresponds to the most considered factor in this group (20 documents). **Capacity of vehicles** refers to the limits of transport capacity depending on the type of vehicle used. This aspect has been mainly considered in optimization models (e.g Rezaei and Kheirkhah [144]; Masoudipour et al. [145]). The second most considered aspect in this group correspond to **Green technology innovation**.

It refers to the investment made in order to improve the environmental performance of the technology used (e.g. Mondal et al. [130]; Saha et al. [113]). The **use of new technology** in recycling networks correspond to the third most considered aspect in this group. For example, Chen et al. [182] analyzed using game theory, the impact of the internet as a new channel of location, collection and negotiation of products/waste. Tong et al. [172] studied the performance of business models based on Information technologies as new ways of collecting waste or products. The use of 4.0 technology has also been explored [206]. Finally, it has been possible to identify in the literature other less considered non process-oriented technological criteria: **Effort to improve the level of technology** [174], **Design for environment products** [124], [125], **Means of transport for waste** and **Sells options of discarded product** ([50]), **Technology transfer** [133], [134], **Research and development for new products** and **Expert decision and skill manpower** [134], **Green rate** [114], **Clean and upgraded technology** [116], **Green innovation** [129], **Technological expertise** [117], **Specialized infrastructure** [136], **Warehouse management**, **Transportation management**, **Inventory management**, **JIT philosophy**, **Information technology (IT)** and **Demand forecasting** [132], **Investment to sustainably improve recovery technology** [112], **Capacity utilization** [115], [184], **Capability of disassembly infrastructure** [115], [184], **Resource Capacity** and **Communication Systems** [118].

In conclusion, considering the number of articles in which the criterion has been considered, capacity of facilities corresponds to the most used among both groups. Considering the groups separately, capacity of facilities, technology selection and recycling rate are process oriented aspects frequently considered. On the other hand, for non-process-oriented criteria, the capacity of the vehicles and the use of new technology are the aspects most considered in the literature. Therefore, all of these aspects must be considered in the analysis.

2.3.2.4 Global analysis

Figure II.12 presents a global analysis of all dimensions. In the figure, the dimension, orientation, main criteria identified for each dimension-orientation, type of indicator (if the criterion has been measured using qualitative or quantitative indicators) and the methodology used are presented. As can be seen in Figure II.12, the social dimension has been considered mainly by worker-oriented criteria. Specifically, job creation corresponds to the most considered criterion. Furthermore, from the point of view of indicators, job creation has been considered quantitatively (number of jobs created) in optimization models. Considering the other orientations for the social dimension (consumer, community or company oriented), the main criteria for these orientations have been considered qualitatively, which have been considered mainly through multi-criteria methods. For the technological dimension, Figure II.12 shows that it has been considered mainly by means of process-oriented criteria. Most of the considered criteria, both for the process-oriented and non-process oriented group, have been evaluated quantitatively. For example, capacity of facilities and capacity of vehicles (the main criteria for each group) have been considered as a maximum amount of product to process and transport respectively. From the methodological point of view, this type of indicators (quantitative) have been considered mainly using optimization, system dynamics or game theory. Finally, for the political dimension, the literature has concentrated mainly on incentive/punishment, emissions and legal policies. The main criteria identified for the incentive/punishment policies and emission policies groups have been considered by means of quantitative indicators. For example, subsidies are considered monetarily (to investment, per product collected, etc), and

the emissions as maximum limits allowed. On the other hand, the legislative criteria have been considered both quantitatively and qualitatively. For example, limits of recyclability, quantity collected, legal context, etc.

Figure II.13 shows the domain in which the main criteria identified for each dimension-orientation have been applied. As can be observed, most of the identified criteria have been applied mainly to the domain of electronic waste, vehicle waste, municipal solid waste, plastic waste, light bulbs waste and waste in general. Considering the social criteria oriented to the consumer, incentives to customers, consumer preference and sensitivity of the customers have been the most considered social factors in recycling networks in general (without specifying domain). On the other hand, the health and safety of consumers have been applied in the domains of e-waste and light bulbs. Regarding the social criteria oriented to the worker, these have been applied in a wide number of domains, where the domains of e-waste, end of life vehicles, tire, plastic and glass stand out. As for the social criteria oriented to companies, all the identified criteria (except stake holders' participation) have been studied in more than one domain. Finally, considering the community oriented social criteria, community complaints, local development and social inclusion, have been considered only in the domain of e-waste. As for the other criteria of this group, they have been measured in more than one recycling domain, where the domain of e-waste recycling stands out. Regarding the criteria for the technological dimension, all the main criteria identified in the process-oriented group have been considered in a wide variety of recycling domains. Specifically, these criteria have been applied mainly in the domains of electronic waste and recycling in general. On the other hand, the use of new technology and green technology innovation have been criteria considered in only two recycling domains (e-waste and household waste for the use of new technology, and end of life vehicles and recycling in general for green technology innovation). Finally, with regards to the political dimension, all the main criteria identified have been considered in more than two different recycling domains, especially in the domains of e-waste and general.

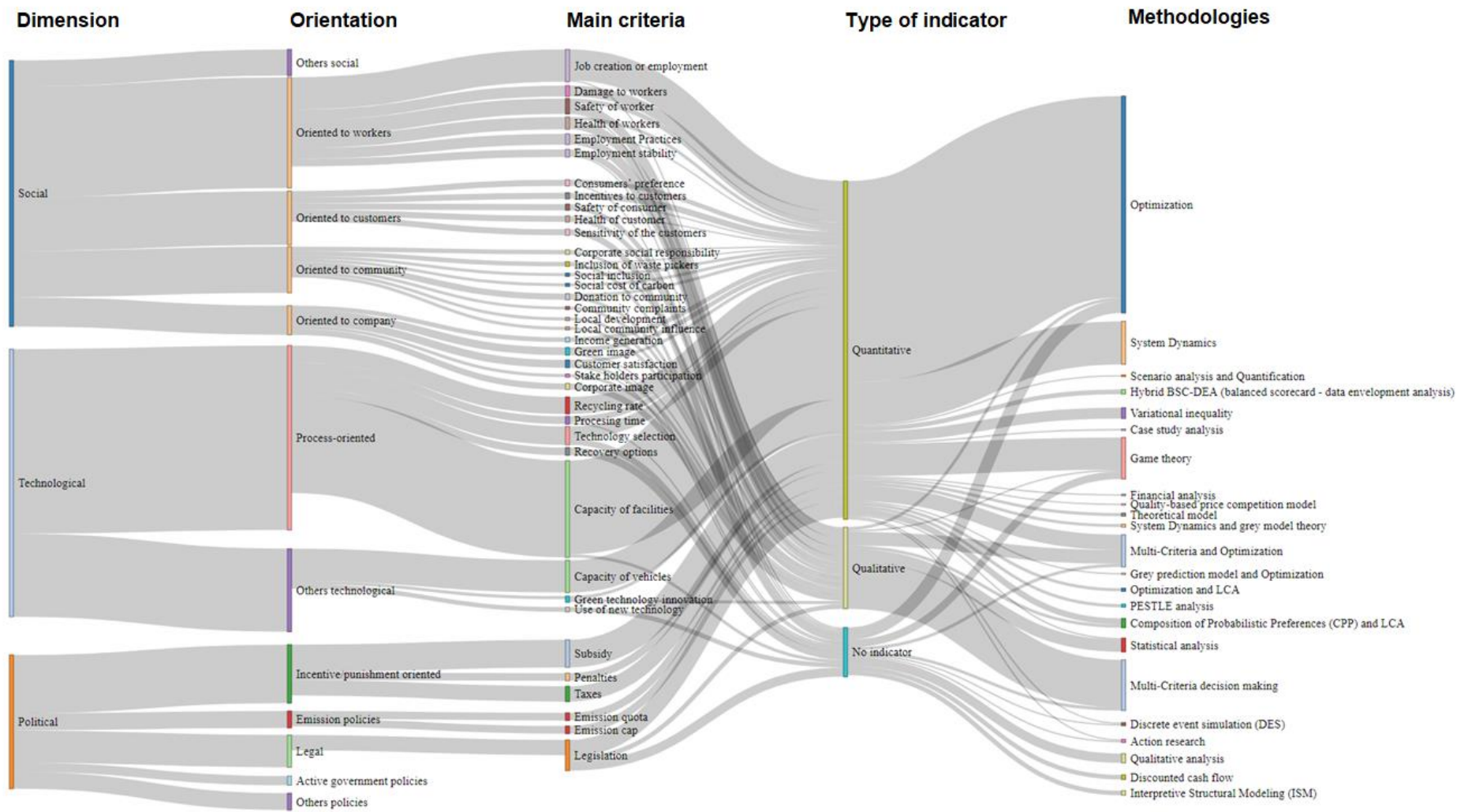


Figure II.12. Global analysis of dimensions, main criteria and methodologies

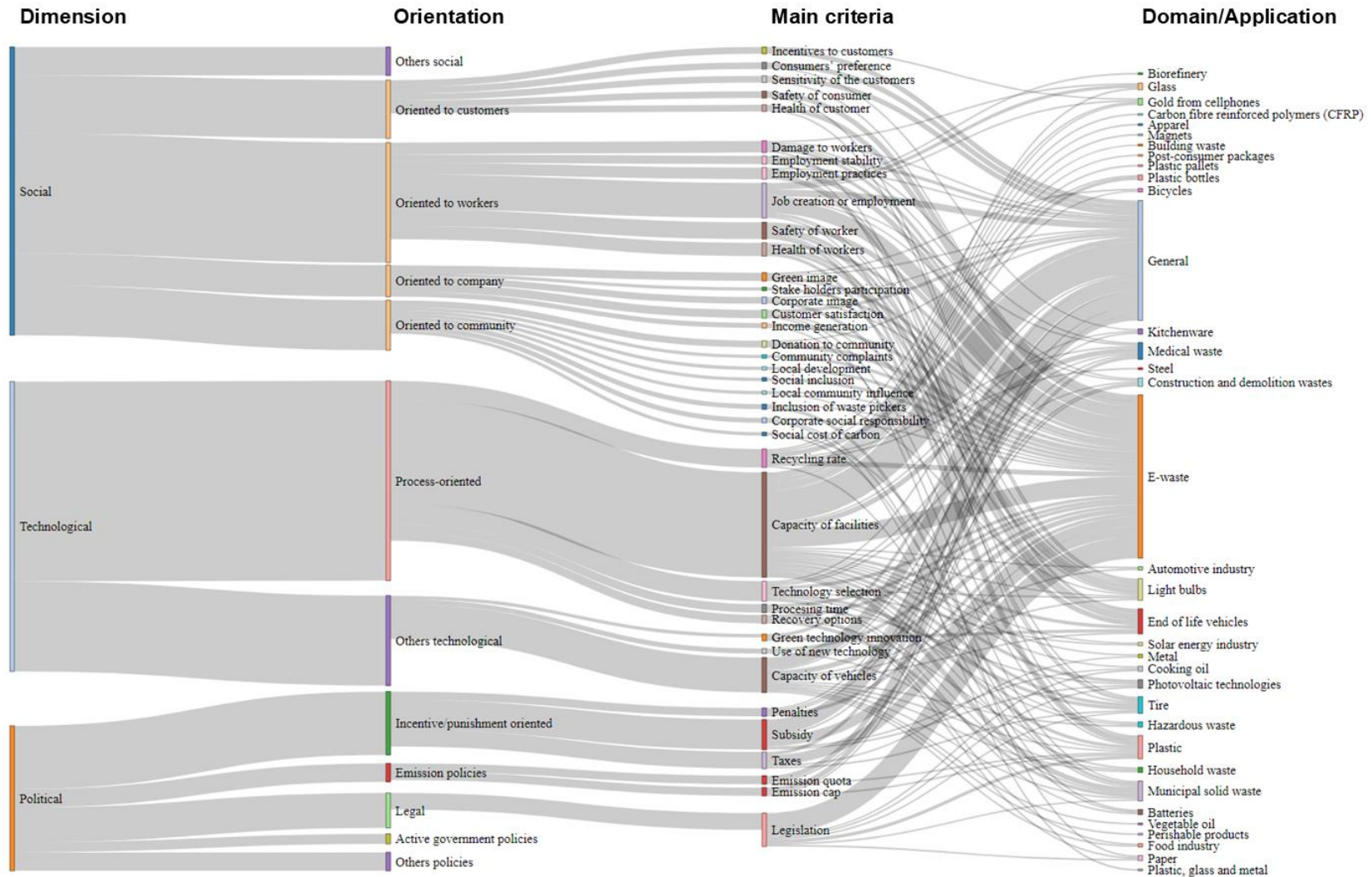


Figure II.13. Global analysis of dimension, main criteria and application domain

2.4. Discussion

Recycling networks such as CLSC and RL-RSC have begun to have a great attention in the literature. In particular, the evaluation of these networks considering aspects of sustainability have been approached in different reviews from different points of view. However, a common conclusion in the literature on sustainability in supply chains networks is the lack of consideration of social, political and technological aspects.

In this study, a systematic analysis of the literature has been carried out in order to know how to consider social, political and technological aspects in the evaluation of recycling networks.

From the analysis of the results, it was possible to observe a growing interest in literature to integrate the three dimensions studied (social, political and technological). From the analysis of the identified criteria for each dimension, it has been possible to identify different perspectives. Considering the social dimension, the found criteria have been classified into five perspectives: Worker-oriented, community-oriented, consumer-oriented, company-oriented and others. Among the social criteria identified, most of them are worker and community oriented. In particular, Job creation or employment is the worker-oriented social aspect most used in the literature studied, which has been mostly considered quantitatively as the number of jobs created. It is also possible to identify other important worker-oriented social criteria, such as the health and safety of workers during the operation. Considering the consumer and community oriented social criteria, there is no a clear criterion to consider. On the one hand, for consumer-oriented social criteria, the health and safety of consumers of recycled products, consumer sensitivity and consumer preference are important consumer-oriented social aspects considered in the literature. On the other hand, for community-oriented social criteria, local development, donation to the community and social inclusion are important aspects considered. For company-oriented social criteria, the image of the company and the customer's satisfaction are the main aspects considered in the literature. Finally, aspects related to social inclusion have been little considered in the literature. However, in the context of recycling, this aspect may be relevant due to the existence of, for example, informal collectors in different countries. Considering the technological dimension, it has been classified in process-oriented and non-process oriented criteria. On the one hand, for process-oriented criteria, the capacity of facilities has been the main criterion considered, which has been represented quantitatively as a maximum amount of product capable of being processed. It has also been possible to identify other process-oriented aspects such as the recycling rate, the processing time and the selection of technology and recovery. The selection of recovery and treatment technology are important qualitative technological factors considered in the context of recycling networks. However, in the selected literature they have been little considered because in most of the articles analyzed, the recovery and processing technology were predefined. Another important process-oriented technological aspect little considered, are the quality of the recovered product, the quality of the recycled product and the conversion rate of materials. For non-process-oriented criteria, the capacity of vehicles has been the main criteria considered, which has been represented quantitatively as a maximum amount of product capable of being transported. Finally, among the articles analyzed addressing the political dimension, it has been possible to identify four types of policies: Incentive/punishment oriented, legal policies, emission policies and active government policies. Among these groups, most policies are of the incentive/punishment type. Specifically, subsidy is the most considered, which has been mainly represented by the amount of money subsidized to the investment or by recycled product. It has also been possible to identify other incentive/punishment-oriented aspects such as penalties and taxes. Another type of policies frequently considered are the legal oriented, which have been presented both qualitatively and

quantitatively. For example, limits of recyclability, quantity collected, legal context, etc. Emission restriction policies have also been a frequently considered policy, where emission quota and emission cap are the main identified criteria for this group. Finally, in a global way, it has been possible to observe criteria considered quantitatively and qualitatively for each dimension. If the criteria are considered qualitatively, the literature has tended to use multi-criteria methods. On the other hand, if the criteria are considered quantitatively, literature has tended to use optimization, systems dynamics or game theory. These last four methodologies (multi-criteria methods, optimization, systems dynamics and game theory) have been identified as the most used in the literature studied in this article. It should be mentioned that the criteria have been grouped by social, political and technological dimension in order to facilitate the analysis. However, these may be related and depend on other dimensions of sustainability. For example, job creation (social dimension) may be related to labor costs (economic dimension). Governmental restrictions on emissions (political dimension) is directly related to the environmental dimension. Aspects related to processing capacity (technological dimension) can directly affect the economic (costs) and environmental dimension.

The evaluation of recycling networks from a sustainability point of view is a requirement today. Economic and environmental aspects in supply networks have been widely considered. However, how to consider social, technological and political aspects of sustainability is not very clear in the literature, especially in the recycling literature. This research gives a basis on the social, political and technological criteria and indicators used in the literature about recycling networks oriented to sustainability. [Table II.3](#) shows a proposal of criteria to be used for each dimension, which have been obtained in this literature analysis. In [Table II.3](#), criteria are proposed based on the number of articles that have been considered (Main criteria), as well as criteria that have not often been considered but, based on the understanding of the criterion, are important in the context of recycling (Suggested criteria). In addition, the proposed main criteria (except local development) have been applied in more than one different recycling domains. These criteria can be used for future research and evaluation of recycling networks offering 1) a more holistic sustainable evaluation and 2) the appropriate criteria for each decision maker involved in the evaluation process. Finally, it is necessary to mention that the analysis of literature carried out in this research corresponds only to evaluation CLSC-RL networks that involve the recycling activity. Therefore, the criteria suggested are limited to this context.

Table II.3. Proposition of integration of social, technological and political dimension

Dimension	Main Criteria	Suggested criteria (to complement the main ones)
Social	Job creation or employment Health and safety of workers Health and safety of consumer Local development Social cost of carbon Donation to community Corporate image Customer satisfaction	Social inclusion
Technological	Capacity of facilities Capacity of vehicles Recycling rate Recovery and Technology selection	Quality of recycled product Quality of returned product Conversion rate
Political	Subsidies to investment or by product recycled Emissions policies (quota and cap) Legal limits (collected, recycled, etc) Penalties and Taxes	

2.5. Summary

In this chapter, a systematic literature review has been carried about social, political and technological dimensions in sustainable recycling network evaluation. A total of 129 journal articles have been selected and analyzed.

This is the first work to carry out a literature review about sustainability evaluation of recycling networks considering these three dimensions (social, technological and political) proposed in the literature. A set of criteria and indicators were identified and analyzed in the literature for each of these three dimensions. From the quantitative point of view, the results have shown the little consideration in the literature of political and technological aspects. From the qualitative point of view, the result of the qualitative analysis process has shown different perspectives/orientations of the criteria for each dimension. For the social dimension, five groups of criteria were identified: worker-oriented, consumer-oriented, community-oriented, company-oriented and others. For the technological dimension, two groups of criteria were identified: process-oriented and non-process oriented. Finally, for the political dimension, five groups of policies have been identified: Incentive/punishment-oriented policies, legal policies, emission policies, active government policies and others. Considering this classification, the literature has tended to consider worker-oriented social aspects, to study incentive/punishment policies, and to consider process-oriented technological aspects. In addition, as a result of the analysis, the main criteria considered in the literature have been identified and proposed for each dimension-orientation. Finally, from the methodological point of view, an important conclusion is the use of methodologies such as optimization, system dynamics and game theory, in case of criteria measured with quantitative indicators, and the use of multi-criteria methods in the case of criteria measured with qualitative indicators.

The detailed analysis carried out in chapters I and II has underlined that integrating social, political and technological dimensions is fundamental to study the feasibility of emerging value chains in general and of the distributed closed-loop recycling in this particular case. Based on the results of this chapter, a set of criteria to be considered for each dimension (social, technological and political) have been suggested to achieve this purpose. Furthermore, the identified criteria have been classified into different orientations. The results obtained in this research can serve as a basis for future studies and evaluations of sustainable recycling networks. In addition, the classification of the dimensions according to different perspectives can serve to find the appropriate criteria not only from the point of view of the sustainability dimension, but also according to the point of view of each of the decision makers and actors who participate in the evaluation process.

The design of a distributed plastic recycling network is a complex project that needs to take into account since the earliest stage a holistic approach including simultaneously the characteristics of a given context and the sustainability dimensions. Under the basis of the previous results, in the next chapter, a new methodology based on modeling approaches and relevant metrics will be proposed for the evaluation of such a project. This methodology would allow decision makers to analyze and potentially define the conditions for the development of sustainable distributed plastic recycling using 3D OS technologies, which is the objective of this thesis.

Chapter III. Proposition of a two-level modelling framework for distributed plastic recycling using 3D open source technologies

3.1 Chapter introduction

In the introduction of this thesis, the need for evaluation tools and methods has been presented in order to assist decision makers in the process of evaluating the implementation of distributed plastic recycling using 3D open-source technologies. The decision process must consider the complexities and barriers of the system under evaluation as well as the requirements of sustainability. In this way, decision makers can analyze the conditions for the development of this plastic recycling approach in a given territory. In [chapter I](#), the literature review on plastic recycling networks showed that studies on the design of plastic recycling networks have been carried out mainly by means of optimization models and life cycle analysis, which mostly consider the economic and environmental dimensions of sustainability. On the other hand, the literature review conducted in [chapter II](#) on technological, social and political dimensions in recycling networks in general, has shown the way in which these three dimensions have been considered. The results have shown that these three dimensions have been integrated using optimization models, game theory, multi-criteria methods and systems dynamics. In order to define the appropriate methodology for the above-mentioned requirements, in this chapter an analysis of the four identified methodologies is conducted. The selected methodology must be able to evaluate the system from the sustainability point of view, considering at the same time the complexities present in it. As a result of the analysis, a two-level modelling approach for the evaluation, from a sustainability point of view, of the distributed plastic recycling approach using 3D open-source technologies is proposed.

3.2 Analysis and selection of methodologies

Before conducting the process of analysis and selection of methodologies, the necessary functionalities of the methodology to be selected must be established. According to the objectives of this research, the methodology must allow the following functionalities: 1) Integration of multiple objectives considering dimensions of sustainability, (2) Integration of qualitative and quantitative aspects in the evaluation, (3) Consideration of the temporality of the parameters in the evaluation and (4) Consideration of logistical/operational implementation decisions. Each condition is explained below:

- **Integration of multiple objectives considering dimensions of sustainability:** The evaluation of sustainability implies the consideration of five dimensions (considering TBL+ approach) and consequently, different criteria. Therefore, it is important that the methodology to be adopted allows the integration of different criteria in order to make a more holistic evaluation.
- **Integration of qualitative and quantitative aspects in the evaluation:** In the context of distributed plastic recycling, besides quantitative aspects (e.g. costs, emissions), qualitative aspects must be considered. These aspects may involve decisions of the recycled filament consumer as well as the decisions of the recycling points regarding the

implementation of facilities. Therefore, it is important that the selected methodology allows the consideration of both aspects.

- **Consideration of the temporality of the parameters:** Due to the fact that the distributed plastic recycling approach is a system that is in development, it is important to consider current and future scenarios in order to analyze the present and future feasibility of this approach. This is why it is important that the methodology allows the consideration of changes in its parameter values over time.
- **Consideration of logistical/operational decisions:** The analysis of the feasibility of distributed plastic recycling, from the point of view of its implementation, involves logistical decisions (decisions regarding machinery to be used, collection routes, means of transport, etc). Therefore, the methodology must also allow the consideration of these types of decisions.

Having defined these functionalities, the process of analysis and selection of methodologies has been conducted. The following subsections presents the process conducted. First, a description and analysis of the identified methodologies is presented. Then, the selection process of the methodology is presented.

3.2.1. Analysis of methodologies

From the literature reviews presented in [chapters I and II](#), four methodologies have been identified as the most widely used: optimization models, game theory, multi-criteria methods and systems dynamics. Each of them is described below.

3.2.1.1. Optimization

Optimization corresponds to the mathematical representation of a problem, where one or more objectives are maximized or minimized taking into consideration different types of constraints of the problem [\[221\]](#). The objective of the problem and its conditions are represented by means of mathematical programming (MP). The most used method of mathematical programming corresponds to the linear programming. However, it is also possible to find other types, for example, integer programming, mixed-integer programming, dynamic programming, network programming, stochastic programming and non-linear programming [\[221\]](#). As mentioned above, the problem to be modelled can be formulated to consider one or more objectives, which may be in conflict. In the case of single-objective problems, we refer to it as single-objective optimization. On the other hand, in case of more than one objective, we refer to multi-objective optimization [\[222\]](#). In terms of solving these problems, the literature offers different exact calculation methods to obtain the optimal solution or solutions. However, if the modeled problem is too complex for the exact methods, it is also possible to find heuristics and approximation algorithms [\[221\]](#), [\[222\]](#).

In the context of plastic recycling, optimization methods have been used in network design and planning, i.e. location of network facilities and material flow between them (e.g. [Aljuneidi and Bulgak](#)

[177], Garai and Roy [120], Hajiaghaei-Keshteli and Fathollahi Fard [147], Papen and Amin [52], Choi and Fthenakis [208]), as well as in vehicle routing problems (VRP) for waste collection (e.g Banyai et al. [206], Aksen et al. [211], Le Blanc et al. [189], Bing et al. [223]). However, as it is a mathematical representation, all the elements considered in the problem must necessarily be represented quantitatively and also require mathematical/functional model which is not always possible (except for heuristic algorithms).

3.2.1.2. Life Cycle Analysis

Life Cycle Analysis is a methodology created in the 1960s, which considers the environmental impact (through different indicators) of a product throughout its life cycle (from resource extraction for its production to its management as waste) [224]. Life cycle analysis considers about fifteen environmental issues, among them: climate change, freshwater use, land occupation and transformation, aquatic eutrophication, toxic impacts on human health, depletion of non-renewable resources and eco-toxic effects from metals and synthetic organic chemicals [224]. Although this methodology has an environmental origin, it has been extended to consider sustainability [224]. For example, for the economic dimension, Life Cycle Costing (LCC) is proposed, which considers all costs associated with the product throughout its life cycle [224]. On the other hand, for the social dimension, social life cycle assessment (S-LCA) is proposed, which considers all social impacts throughout the product's life cycle [224].

In the context of recycling, LCA has been used to evaluate the environmental impact of recycling systems implementation [94], [95], [97], [102] and to evaluate waste management options [96]. However, these studies have considered previously defined scenarios/alternatives, which may be considered a limitation of this methodology. In addition, this methodology is strictly quantitative and the consideration of the temporality of the parameters is possible, but very complicated [224].

3.2.1.3. Multi-criteria/Multi-attribute methods

Multi-attribute methods are tools used for decision making given a set of predetermined alternatives. In the analysis, the preference of decision makers (or stakeholders) is considered in terms of the criteria used to make the decision, which may be in conflict [225], [226]. As a result, relative weights are obtained for each criterion, which, in combination with the values of the criteria for each alternative, they can be evaluated and eventually ranked. Multi-criteria methods allow for the consideration of both qualitative and quantitative criteria. In the context of recycling, these methods have been used for the selection of recycling suppliers (e.g Mavi, Goh and Zorbakhshnia [74], Kafa, Hani and El Mhamedi [136]) or for the selection of the best recovery option (e.g Ahmed, Ahmed, Md Rezaul Hasan Shumon et al.[134], Jindal and Sangwan [135], Ahmed, Ahmed, Md Rezaul Hasan Shumon et al. [133]). Although their relevance, the limitation of this methodology is that the alternatives for selection must be previously defined and does not consider the temporality in the criteria.

3.2.1.4. Game theory

Game theory corresponds to the mathematical representation of the interactions between decision makers who participate in a problem or dilemma [227]. These actors must make decisions considering the decision of other agents and a set of conditions [227]. In game theory, it is assumed that each agent is a conscious entity and that they interact to obtain their own benefit [227]. In the context of recycling, this methodology has been used to analyze the interaction between the actors that make up a recycling network (e.g. collector, recycler, manufacturer, etc). These actors must make decisions such as the purchase and sale price of the material along the chain (e.g. Ghalekhondabi and Ardjmand [112], Han, Shen and Bian [154], Chen, Wu and Li [182], Modak et al. [63]). A limit of this methodology is that all its parameters must be represented quantitatively.

3.2.1.5. System Dynamics

System Dynamics is a tool created during the 1960's by Forrester [228] to model complex systems. This methodology proposes the qualitative and quantitative representation of the system [13]. Qualitatively, the system is represented by means of causal link and causal loops (positive or negative) between the elements of the system [13]. Then, quantitatively, it uses control theory by means of stock and flows to mathematically represent the relationships [13]. Finally, through simulations, it tries to predict the behavior of the system. These simulations allow establishing scenarios in order to facilitate decision making and the search for solutions to the modeled problem. In the context of recycling, this methodology has been used to analyze the impacts, from the point of view of sustainability, of different recycling networks (e.g. Chaudhary and Vrat [11], Georgiadis and Besiou [125]). It has also been used to analyze the impact of different recycling policies (e.g. Ghisolfi et al., [127], Besiou, Georgiadis and Van Wassenhove [126]).

In this section, a description and analysis of the methodologies has been presented. The following section presents the process and criteria established for the selection of the appropriate methodology for this research.

3.2.2. Selection of methodologies

After analyzing the advantages and disadvantages identified for each methodology, a selection based on criteria has been conducted. As selection criteria, the established conditions have been considered (Integration of multiple objectives considering dimensions of sustainability, Integration of qualitative and quantitative aspects in the evaluation, Consideration of the temporality of the parameters and Consideration of logistical/operational decisions). The selected methodology should be able to meet all the requirements defined above in order to be able to support the decision making process during the evaluation of implementation of distributed plastic recycling.

As a result of the methodology selection based on the established criteria (see Table III.1). Life Cycle Analysis, Multi-criteria analysis and Game theory have been discarded. Game theory has been discarded mainly due to the complexity in the integration of multiple objectives and the impossibility of considering qualitative aspects. In addition, game theory methodology is oriented to the analysis of the decisions due to the interaction between the actors, which is not the objective of this research. On

the other hand, multi-criteria analysis has been discarded because it does not consider the temporality in the parameters, an important characteristic for this research. Finally, Life Cycle Analysis has been discarded mainly because it does not allow the integration of qualitative aspects in the evaluation, it need predefined alternatives to evaluate and does not allow consideration of all the logistical decisions required during implementation evaluation. In addition, the literature indicates that Social Life Cycle Assessment "is still in its infancy" [224].

As selected methodologies, optimization and system dynamics have been considered. Optimization has been selected because it allows to consider the most important aspects for the implementation evaluation: integration of multiple objectives considering sustainability dimensions, consideration of the temporality of the parameters in the evaluation and consideration of logistic decisions of implementation. However, this methodology only allows to consider quantitative aspects. For this reason, systems dynamics has been considered as a complementary methodology, because, besides allowing the integration of multiple objectives and the temporality of the parameters, it allows the consideration of qualitative and quantitative aspects as well as modeling complex systems considering sustainability approach. Additionally, this methodology could be used to propose future scenarios, which could be evaluated by means of optimization models.

Table III.1. Comparison of methodologies

Method	Integration of multiple objectives considering sustainability dimensions	Integration of qualitative and quantitative aspects in the evaluation	Consideration of the temporality of the parameters	Consideration of logistical decisions
Optimization	Yes	No	Yes	Yes
Life Cycle Analysis	Yes	No	Yes	No
Multi-criteria methods	Yes	Yes	No	Yes
Game theory	Yes	No	Yes	Yes
Systems dynamics	Yes	Yes	Yes	No

In conclusion, two methodologies (optimization and system dynamics) have been selected to be used in the evaluation of distributed plastic recycling for 3D printing. The following section presents the proposed framework considering both methodologies.

3.3 Presentation of the two-layer modeling approach

The modeling and evaluation approach proposed in this research consists in a combination of two points of view and respective methodologies: the system point of view and the operational point of view (see Figure III.1). For the system viewpoint, modelling using system dynamics methodology is proposed. On the other hand, for the operational point of view, the optimization approach is proposed. This two-layer evaluation approach is suggested in order to consider, by means of dynamic systems, those aspects that are not possible to consider by means of an optimization model. For example, policy implementation or citizens' attitudes towards plastic recycling. Each level and point of view is explained below.

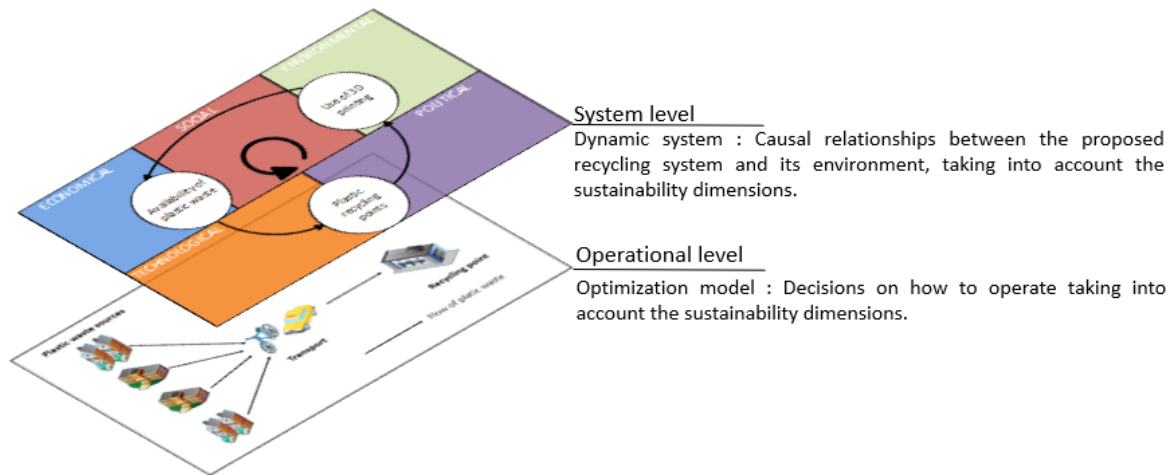


Figure III.1 : Two-layer modeling approach for distributed plastic recycling using 3D open source technologies

3.3.1. Level 1: Operational level

At the operational level, the system is evaluated from a logistical point of view. Under this point of view, the system is evaluated considering at the same time those operational decisions that must be taken. For example, decisions regarding the placement of recycling facilities, collection frequency and treatment of plastic waste at the recycling point (see [Figure III.2](#)).

The results of the literature review on plastic recycling networks ([Chapter I](#)), showed that the optimization approach is the most used for the evaluation of this type of networks. However, the literature on plastic recycling networks has only considered the centralized approach, that is to say, the distributed plastic recycling approach has not been addressed from a logistical point of view.

In the context of distributed plastic recycling, different logistical decisions should be made for each recycling point of the network, e.g. the location of each recycling point and their collection route. In this sense, the problem to deal with can be defined as a location-routing problem. Location routing problems are those for which it is necessary to decide simultaneously the location of facilities and the route of vehicles (VRP) [229]. A total of 16 articles ([57], [148], [229]–[242]) addressing a location-routing problem for recycling were found. From the perspective of the structure of the networks studied, these consist of networks wherein the collection phase is carried out by means of distributed centers. From there, the flow of material between collection and recycling (or other options such as incineration) tends to be centralized using intermediate treatment and sorting facilities. From the methodological point of view, most articles use a mono-objective MILP modeling type ([57], [229], [230], [232], [236], [237], [239], [240]) or multi-objective modeling ([148], [231], [233]–[235], [238], [241], [242]), which correspond to the modeling approach proposed for this layer.

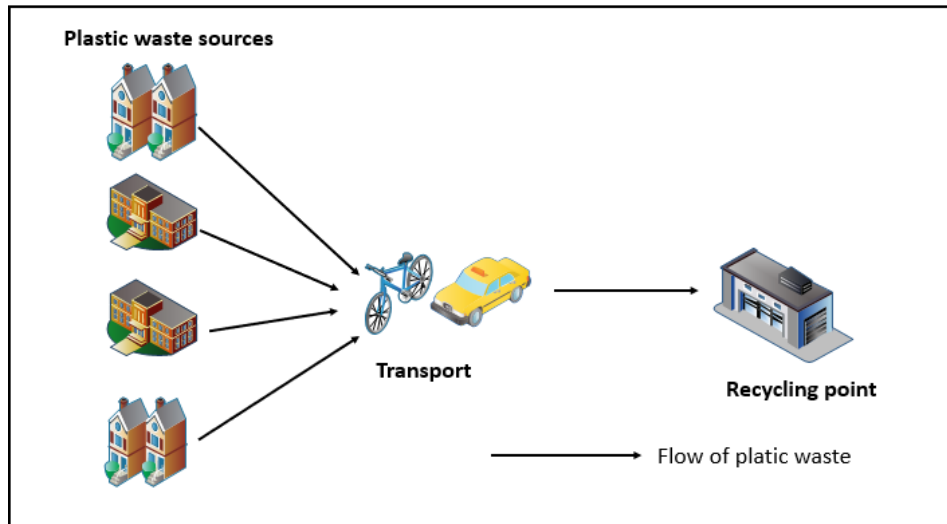


Figure III.2. Operational level

3.3.2. Level 2: System Level

The system level, tries to consider the interaction between the proposed system and its environment (see Figure III.3). Figure III.3 represents the interaction between the proposed plastic recycling system and its context (availability of waste and use of 3D printing) considering the sustainability dimensions (economic, social, environmental, political and technological). As examples of the dependence of the system on its context, the system should consider the policies implemented to promote plastic recycling and the use of 3D printing (political dimension), the attitude of citizens towards plastic recycling and the use of 3D printing (social dimension), the development of 3D printing and extrusion machine (technological dimension), as well as the economic feasibility and environmental benefits of implementing small plastic recycling facilities.

From the methodological point of view, the system dynamics approach is proposed. This methodology has been used in the literature in order to consider political, social and technological aspects. For example, Besiou, Georgiadis and Van Wassenhove [126] studied the impact, from a sustainability point of view, of the inclusion of informal collectors in the formal e-waste recycling system. In their study, they consider aspects such as: legislative limits around recycling (political), unemployed people (social) and recyclability rate (technological). Chaudhary and Vrat [11] study the benefits, from the point of view of sustainability, of gold recovery from cell phones in India. In their study, they consider aspects such as job creation and incentives paid to consumers if they handover the discarded cellphones via formal recovery channels (social), and recycling rate (technological). Other similar examples can be found in the literature [124], [125], [127], [213].

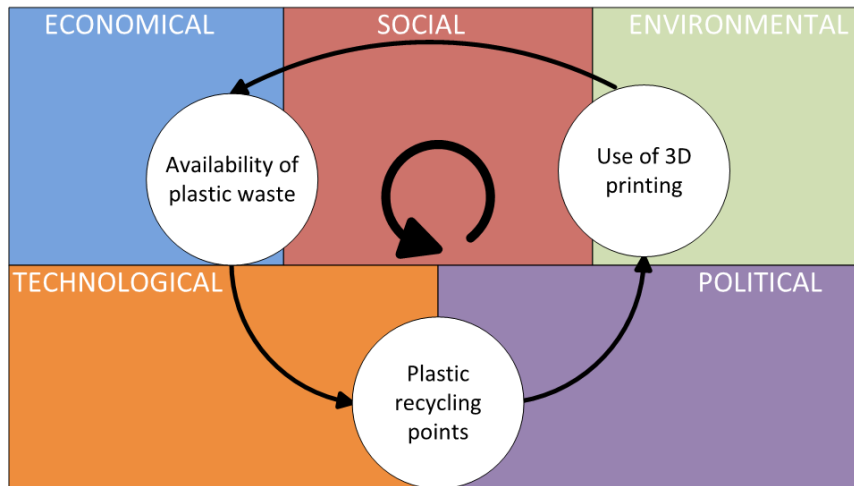


Figure III.3. System level.

3.4 Summary

In this chapter, the process of analysis and selection of methodology for the evaluation of distributed plastic recycling has been presented. As a result, a two-layer framework has been proposed. It is based on the combination of two points of view: system point of view and operational point of view. This modelling approach proposes the use of dynamic systems for the system perspective, and optimization models for the operational perspective. This framework has been proposed in order to consider, by means of system dynamics, aspects that are not possible to consider by means of an optimization model (for example, the involvement of citizens in the proposed recycling system, sensitivity of 3D printing users regarding the use of recycled plastic filament, development of 3D printing technologies to be used in the system, etc).

In the next chapters ([chapter IV](#) and [V](#)), the models developed for each layer and their application to a case study are presented. First, the optimization model is presented in [chapter IV](#). Then, the system dynamic model developed is presented in [chapter V](#).

Chapter IV. Operational level: A mono-objective optimization model for the evaluation of a distributed plastic recycling network.

4.1 Chapter introduction

In this chapter, the mathematical optimization model developed for the economic and environmental evaluation of distributed plastic recycling is presented, which corresponds to the second layer of the proposed analysis and modeling approach. The model developed corresponds to a mono-objective optimization model type Mixed Integer Linear Programming (MILP). The variables used, the objective function and the restrictions are presented. The model developed has been applied to a case study. A sensitivity analysis has been conducted to validate the coherence of the model. The results are presented and discussed.

4.2 Description of the problem to be modeled

The aim of the proposed model is to identify the optimal configuration of the distributed CLSC plastic recycling network, taking into account a particular context defined in [Fig. V.1](#). The context defines various fixed elements, such as:

1. A set of geographically distributed sources of polymer waste, with a distance from the recycling point and between them, and a given volume and weight of polymer waste.
2. A recycling point with a limited plastic recycling capacity, determined by the capacity of the recycling machine and working time. The costs and emissions derived from the use of the recycling machine are also taken into account.
3. A means of transport to carry out the collection, with a transport capacity limited by weight and volume. Including the costs and emissions for the collection activity, with a specified travel speed and working time.

In order to simplify the model, we can suppose that one type of relatively “clean” plastic waste ([Cruz Sanchez \[243\]](#)) is collected and transported from the various sources. Plastic wastes with these characteristics can be found for example in prototyping cases. So only the following types of decisions have to be made by the user.

1. The number of polymer waste sources from which polymer waste must be collected.
2. The number of collection routes required.
3. The sequence of the collection routes.
4. The means of transport to be used on each route.

Considering the above assumptions, the objective function will be represented by the economic and environmental benefits or savings. The savings are calculated comparing the cost obtained by the two proposed supply loop networks with and without distributed recycling (Fig. V.1).

Proposed supply loops for open source 3D printers

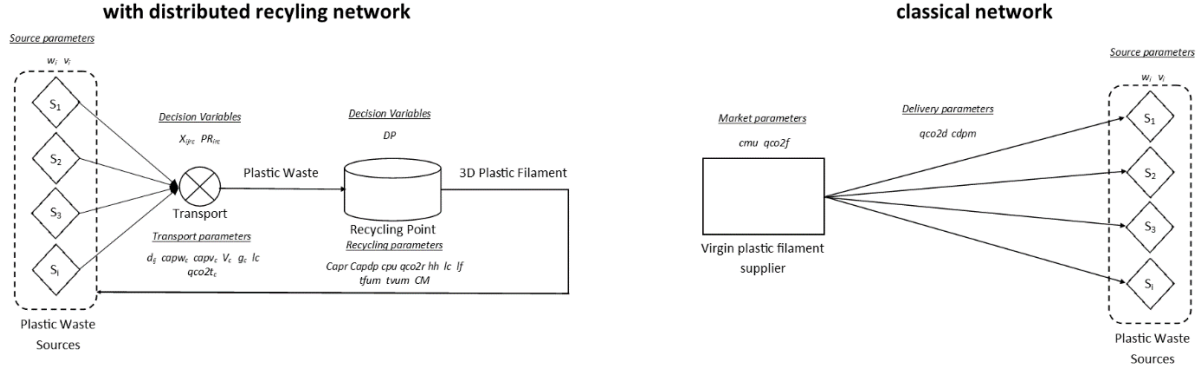


Figure IV.1. Conceptual model of the recycling network [244]

4.3 Presentation of the mono-objective optimization model

Table IV.1, IV.2 and IV.3 shows respectively the nomenclature for the representation of sets, decision variables and parameters. As previously mentioned, the optimization model developed corresponds to a Mixed Integer Linear Programming (MILP) type where the objective functions and constraints are represented linearly, i.e., the decision variables are vectorially independent.

Table IV.1. Sets

Set	Description	Symbol	Indices
Set of points	These are all the points where 3DP plastic wastes are produced for later recycling in the recycling point. The recycling point is also considered inside this set	I	i= 1,2,...,I
Means of transport	All available means of transport in the recycling point to realize the collection.	C	c= 1,2,...,C
Set of route	All available means of transport in the recycling point to realize the collection	R	r= 1,2,...,R

Table IV.2. Nomenclature of decision variables

Symbol	Description	Type
X_{ijrc}	1, if use path from the collection point i to j	Binary
PR_{irc}	1, if the beginning point i is associated with the route r and transport c	Binary
DR_{jrc}	1, if the destination point of path j is associated with the route r and transport c	Binary
U_i	Sequence order in which the point i is visited, excluding the point of origin (functional variable used in a restriction of routing)	Integer
DP	Days needed to process the collected plastic waste	Integer

Table IV.3. Nomenclature of parameters

Group	Parameter	Symbol	Unit
Means of transport (c)	Capacity transportation	$capw_c$	kg
	Volume capacity	$capv_c$	L
	Mean speed for collection	V_c	km/h
	Variable cost to carry out the collection	g_c	€/km
Plastic waste	Weight at point i	w_i	kg
	Volume at point i	v_i	L
	Distance between collection points i and j	d_{ij}	Km
Recycling point	Capacity of recycling of the recycling point in the period considered	$Capr$	Kg
	Distance between recycling point i and collection point j	d_{ij}	Km
	Daily processing capacity of the recycling point	$Capdp$	Kg
	Quantity of daily work in the recycling point	hh	h
	Variable time of use of machine	$tvum$	h/kg
	Fixed time for machine initialization	$tfum$	h/day
	Loss factor of mechanical recycling	lf	%
Economical	Delivery cost of plastic filament on the market	c_dpm	€/kg
	Cost of a unit of virgin plastic filament on the market	cmu	€/kg
	Cost of the treatment of recycling and generating a unit of recycled plastic filament	cpu	€/kg fil.rec
	Price of a unit of emitted CO ₂	pem	€/kg CO ₂ eq.
	Labor cost per hour of work	lc	€/h
	Amortization cost of the machines in the period considered	CM	€
Environmental	CO ₂ emitted by delivery of virgin plastic filament to the recycling point	$qCO2_d$	kg CO ₂ eq./kg fil.virgin
	CO ₂ emitted per unit of virgin plastic manufactured	$qCO2_f$	kg CO ₂ eq./kg virgin
	CO ₂ emitted per unit of plastic recycled	$qCO2_r$	kg CO ₂ eq./kg recy
	CO ₂ emitted by the means of transport c	$qCO2_t$	kg CO ₂ eq. /km

In the next paragraph, two main elements are presented: the objective function and restrictions of the model.

4.3.1. Objective function

As stated above, the objective function of the mathematical model is represented as a benefit for maximization and is modeled from two perspectives: (1) Economic and (2) Environmental.

Similar to other authors, where economic and environmental costs are integrated into a single objective function ([70], [73], [106]), the objective function is modeled as a maximization of the sum of Economic Benefit and Environmental Benefit.

4.3.1.1. Economic Benefit

The Economic Benefit (EB) corresponds to the quantity of money saved as a result of to the recycling a quantity of plastic waste which is converted into filament for 3D printing. The EB is computed as the difference between the costs of recycled and virgin filament. The Procurement Cost (PC) includes the filament price of purchase on the market and the delivery cost. The Cost of Recycling

(CR) corresponds to the cost of obtaining the plastic filament by recycling the amount of plastic waste, which considers the labor and transport cost of the plastic waste collection, and the labor and processing (recycling) cost of plastic waste as represented in [Figure V.1](#).

$$\begin{aligned}
 \text{Economic Benefit} = (PC - CR) = & \left(\sum_{i \in I} \sum_{c \in C} \sum_{r \in R} w_i * PR_{irc} * \left(1 - \frac{lf}{100}\right) * (cmu + cdpm) \right) \\
 - & \left(\sum_{i \in I} \sum_{j \in I} \sum_{c \in C} \sum_{r \in R} X_{ijrc} * d_{ij} * \left(g_c + \frac{1}{V_c} * lc\right) + \sum_{i \in I} \sum_{c \in C} \sum_{r \in R} w_i * PR_{irc} * (cpu + tvum * lc) + (DP \right. \\
 & \left. * tfum * lc) + CM \right) \quad (1)
 \end{aligned}$$

4.3.1.2. Environmental Benefit

The Environmental Benefit corresponds to the quantity of carbon dioxide emissions equivalent avoided as a result of recycling a quantity of plastic, expressed in monetary units [9], [10]. More precisely, it corresponds to the difference between the quantity of emissions due to 1) the manufacturing process and transport of a quantity of commercial 3D plastic filament, and 2) the quantity of emissions due to local recycling (collection and manufacturing) of the same quantity of matter to obtain 3D plastic filament. The mathematical structure of this part of the objective function is shown in eq.(2).

Environmental Benefit =

$$\begin{aligned}
 & \left(\sum_{i \in I} \sum_{c \in C} \sum_{r \in R} w_i * PR_{irc} * pem * (qCO2_f + qCO2_d) \right) \\
 & - \left(\sum_{c \in C} \sum_{i \in I} \sum_{r \in R} w_i * PR_{irc} * qCO2_r * pem \right. \\
 & \left. + \sum_{i \in I} \sum_{j \in I} \sum_{c \in C} \sum_{r \in R} X_{ijrc} * d_{ij} * qCO2_t * pem \right) \quad (2)
 \end{aligned}$$

4.3.2. Restrictions

The restrictions used in the model are related to the characteristics or conditions associated with (1) the collection route, (2) the means of transport used, (3) the processing capacity, and (4) the non-negativity of variables. These terms are explained below.

4.3.2.1. Route restrictions

Route restrictions are considered in order to integrate characteristics into the routes generated by the modeled solution. For example, that the established route must start and end at the recycling point, that each route must have only one means of transport associated with it, etc.

Eq. (3) ensures that each chosen collection point is associated with only one route and means of transport. Eq. (4) ensures that the route and means of transport used to arrive at a certain point are the same route and means of transport used to reach other points. Eqs. (5) and (6) ensure that a means of transport and route arrive and leave only once from that point if it was elected by the model, and never if it was not elected. Eqs. (7) and (8) ensure that a means of transport and route arrive and leave only once from the recycling point if the route and means of transport are used. Finally, Eq. (9) avoids sub-tours between points of collection.

$$\sum_{c \in C} \sum_{r \in R} PR_{irc} \leq 1, \quad \forall i \in I - \{\text{Recycling point}\} \quad (3)$$

$$DR_{jrc} = PR_{irc}, \quad \forall r \in R, \forall c \in C, \forall i \in I - \{\text{Recycling point}\}, \forall j \in I - \{\text{Recycling point}\}, i = j \quad (4)$$

$$\sum_{j \in I} x_{ijrc} = PR_{irc} \quad \forall i \in I - \{\text{Recycling point}\}, \forall c \in C, \forall r \in R \quad (5)$$

$$\sum_{i \in I} x_{ijrc} = DR_{jrc} \quad \forall j \in I - \{\text{Recycling point}\}, \forall c \in C, \forall r \in R \quad (6)$$

$$\sum_{j \in I} \sum_{c \in C} x_{ijrc} \leq 1 \quad i = \text{Recycling point}, \forall r \in R \quad (7)$$

$$\sum_{i \in I} \sum_{c \in C} x_{ijrc} \leq 1 \quad j = \text{Recycling point}, \forall r \in R \quad (8)$$

$$U_i - U_j + n * x_{ijrc} \leq n - 1 \quad \forall i \in I - \{\text{Recycling point}\},$$

$$\forall j \in I - \{\text{Recycling point}\}, r \in R, c \in C \quad i \neq j \quad i, j = 1 \dots n \quad (9)$$

4.3.2.2. Restrictions on means of transport

Restrictions on means of transport are considered in order to integrate their characteristics into the model solution. For example, that the amount of plastic waste collected by the means of transport on a given route should not exceed its transport capacity.

Eqs. (10) and (11) ensure that the weight and volume of the amount of plastic waste collected on each route do not exceed the capacity used for each route (weight and volume respectively). On the

other hand, Eq. (12) ensures that the working time to carry out the collection cannot exceed the number of daily working hours.

$$\sum_{i \in I} w_i * PR_{irc} \leq capw_c \quad \forall r \in R, c \in C \quad (10)$$

$$\sum_{i \in I} v_i * PR_{irc} \leq capv_c \quad \forall r \in R, c \in C \quad (11)$$

$$\sum_{i \in I} \sum_{j \in I} \sum_{r \in R} x_{ijrc} * d_{ij} \leq hh * V_c \quad \forall c \in C \quad (12)$$

4.3.2.3. Restriction on capacity of processing (recycling)

A restriction of processing capacity is considered in order to integrate the characteristics of the recycling point in the modeled solution. For example, that the total amount of plastic waste collected does not exceed the processing capacity of the recycling point in a given period of time

Eq. (13) ensures that the total amount collected is not greater than the processing capacity of the recycling point. Eqs. (14) and (15) ensure that the number of processing days needed is correctly related to the amount to collect.

$$\sum_{r \in R} \sum_{c \in C} \sum_{i \in I} w_i * PR_{irc} \leq Capr \quad (13)$$

$$\sum_{r \in R} \sum_{c \in C} \sum_{i \in I} \frac{w_i * PR_{irc}}{Capdp} \leq DP \quad (14)$$

$$\sum_{r \in R} \sum_{c \in C} \sum_{i \in I} \frac{w_i * PR_{irc}}{Capdp} + 1 \geq DP \quad (15)$$

4.3.2.4. Restriction of non-negativity.

These types of constraints are considered in order to specify the characteristics of the variables considered in the model.

Eqs. (16) and (17) ensure that both the Economic Benefit and Environmental Benefit (expressed in equations (1) and (2) respectively) do not take negative values. Eq. (18) represents binary constraints. Eqs. (19) and (20) are non-negative constraints.

$$Economic\ Benefit \geq 0 \quad (16)$$

$$Environmental\ Benefit \geq 0 \quad (17)$$

$$x_{ijrc}, PR_{ic}, DR_{jrc} : \text{binary } \forall i \in I, j \in J, r \in R, c \in C \quad (18)$$

$$U_i \geq 0 \text{ and integer} \quad (19)$$

$$DP \geq 0 \text{ and integer} \quad (20)$$

A mathematical model for a distributed CLSC plastic recycling network for OS 3D printing technologies was presented. In the next section, the application of the mathematical model is illustrated through a case study.

4.4 Application of the proposed optimization model

The model has been applied considering as a case study the city of Nancy located in the region of Lorraine, France. The Lorraine Region has a program to support the integration and diffusion of 3D printing technologies into secondary schools. To achieve this goal, an investment program has been established in order to provide each secondary school with 3D printers within the academic program²³. Given this context, since 2014, the Lorraine Fab Living Lab (LF2L), the innovation platform of the ERPI laboratory within the framework of a multi-disciplinary project “the GreeFabLab²⁴”, is considering the implementation of a local plastic recycling to supply recycled filament to schools and high schools of Nancy.

In order to define, from a logistical point of view, the optimal way in which a plastic recycling network should operate in this type of facility, the proposed model is applied. The aim of the recycling network is to collect PLA plastic waste from a sample of secondary schools and high schools of Nancy city. The reason why this network is suitable for this research resides on the fact that the used PLA could be collected at the source as a “clean” waste before it will be mixed to other waste streams. This will allow us to avoid the sorting stage which is one of the most time consuming and costly operations.

Based on information obtained in relation to secondary schools already using 3D printers, to address the feasibility thereof, the following assumptions were considered:

- Based on a survey²⁵ applied to different school teachers of the Lorraine region during the period of November 2018, within the framework of this research. It is known that currently 2 of the 23 schools and high schools in the city have 3D printers. For the 21 schools without 3D printers, it will be assumed that they will have 2 3D printers each in a near future. This amount corresponds to the average number of printers that schools and high schools in the Lorraine region currently have.

²³ F. Robine and R. Tomasini, “Le ‘FabLab’, un incubateur de créativité et d’innovation. La lettre de la pédagogie 6.,” 2018.

²⁴ <http://lf2l.fr/projects/green-fablab/>

²⁵ https://docs.google.com/forms/d/e/1FAIpQLSf_EWlqMFUA22UZjX-gMTTg0l9mcZVr-sDO5JhjfVzjZLFqCA/viewform?usp=sf_link

Table IV.4. Amount of PLA plastic waste per school / high school

School / High schools	Number of printers	Kilograms of monthly PLA plastic waste
Lycée professionnel Paul Louis Cyffle	2	0.346
Collège/Lycée Charles De Foucauld	2	0.346
Lycée professionnel Claude Daunot	2	0.346
Collège/Lycée Saint Dominique	2	0.346
Lycée général et technologique Jeanne D'Arc	2	0.346
Collège/Lycée Notre Dame Saint Sigisbert	1	0.173
Collège Alfred Mezieres	2	0.346
Lycée professionnel Les Métiers De La Beauté	2	0.346
Collège La Craffe	2	0.346
Lycée général et technologique Henri Poincare	2	0.346
Collège Guynemer	2	0.346
Lycée général et technologique Henri Loritz	5	0.865
Collège/Lycée Saint Leon Ix	2	0.346
Collège Louis Armand	2	0.346
Lycée professionnel Marie Immaculee	2	0.346
Collège Du Sacre Cœur	2	0.346
Collège/Lycée Frederic Chopin	2	0.346
Lycée technique Compagnie De Formation-Pigier	2	0.346
Collège/Lycée général et technologique Georges De La Tour	2	0.346

Table IV.5. Parameters considered for the case study.

Group	Parameter	Value	Reference
Means of transport	Car capacity (Volume)	254 L	Suzuki Motor Corporation ²⁶
	Car capacity (Kg)	415 kg	Suzuki Motor Corporation ²⁶
	Car speed	21 km/h	Average speed between cities using Google maps (Appendix IV.2)
	Variable cost of the car (gasoline and amortization)	€ 0.15 /km	LF2L
	Motorcycle capacity including box (volume)	78 L	Suzuki Moto France ²⁷
	Motorcycle capacity including box (kilograms)	17 Kg	Estimation based on weight-volume relation (4.58 L/kg)
	Motorcycle speed	21 km/h	Average speed between cities using Google maps (Appendix IV.2)
	Variable cost of the motorcycle (gasoline and amortization)	€ 0.15 /km	LF2L
Recycling point	Daily recycling capacity	1.75 kg/ day	LF2L
	Capacity of recycling in the period considered	35 kg/month	LF2L
	Variable human time intervention	3 min/kg of plastic waste	LF2L
	Daily human time maintenance	15 min/day	LF2L
	Daily labor hours	7 h/day	LF2L
	Loss factor of mechanical recycling	10 %	LF2L

²⁶ Suzuki Motor Corporation, "Small Car Loaded with Big Ideas," 2014. [Online]. Available: <https://www.globalsuzuki.com/automobile/lineup/celerio/index.html>. [Accessed: 20-Dec-2018].

²⁷ Suzuki Moto France, "Burgman 125," 2018. [Online]. Available: <https://www.suzuki-moto.com/gamme-2018/burgman-125>. [Accessed: 20-Dec-2018].

Table IV.5. Parameters considered for the case study. (Continuation)

Group	Parameter	Value	Reference
Economic	Amortization cost of the machine	€ 42.95/month	LF2L
	Cost of purchase of plastic filament	€ 19.99 / kg	Atome3D ²⁸
	Cost by delivery of plastic filament	€ 0	Not considered due to existing offers on the market without delivery costs.
	Cost of recycled plastic	€ 0.88/ kg of plastic waste	[27]
	Price of CO ₂ emission	€ 20/ton	[10]
	Labor cost	€ 17/ h	LF2L
Environmental	CO ₂ emitted by manufacturing virgin plastic	1.8 kg of CO ₂ eq / kg of plastic	[245]
	CO ₂ emitted by plastic recycling	0.52 kg of CO ₂ eq / kg of plastic	[14]
	Distance considered for delivery transport (United States to France)	7661 km	Google maps
	Emission of delivery transport of plastic filament per kilometer	0.552 kg of CO ₂ / t / km	[246]
	Emission of delivery transport of plastic filament	4.229 kg of CO ₂ / kg of plastic	[246]
	Car emissions	99 g of CO ₂ /km	Suzuki Motor Corporation ²⁶
	Motorcycle emissions	68 g of CO ₂ /km	Suzuki Moto France ²⁷

4.5 Results

The optimization model was programmed and solved using GAMS-CPLEX software. The model was run on a server with a 2.4 GHz Intel Core i7 processor and 16 GB of RAM.

In order to find out whether the solution obtained is global optimal or not, it is necessary to observe the absolute and relative optimality criteria (absolute and relative gap). The absolute gap corresponds to the difference between the best possible integer solution (considering the relaxation performed by the algorithm of Branch and Cut using restrictions²⁹) and the current best integer solution^{30,31}. The relative gap represents the relative difference between the best possible integer solution and the current best integer solution. Based on these criteria, a solution is global optimal when the best possible integer solution and the current best integer solution are equal, which makes these criteria equal to zero^{30,31}.

The results of the solution obtained for the objective function (Eq. (1) and Eq. (2)) and the parameters of the model (Table IV.5) are shown in Table IV.6. A time tolerance of two hours of calculation was used. A total benefit of €46.25 per month was obtained, which corresponds to the sum

²⁸ "Atome3D." [Online]. Available: <https://www.atome3d.com/collections/filaments-pla/products/raise3d-pla-colorful-blanc-white-1-75mm-1kg?variant=32670721048714%0A>.

²⁹ IBM Knowledge Center, "Branch & cut or dynamic search?" [Online]. Available: https://www.ibm.com/support/knowledgecenter/SSSA5P_12.6.0/ilog.odms.cplex.help/CPLEX/UsrMan/topics/discr_optim/mip/performance/13_br_cut_dyn_srch.html. [Accessed: 09-Jan-2019].

³⁰ G. D. Corporation, "GAMS – Documentation," no. October. 2018.

³¹ I. E. Grossmann, A. Vecchietti, and E. Kalvelagen, "GAMS / DICOPT : A Discrete Continuous Optimization Package DICOPT solves models of the form : " pp. 1–20, 2003.

of the monthly Economic Benefit and Environmental Benefit, with values of €45.39 per month and €0.86 per month respectively. Considering the optimization method used²⁹, the result obtained has a 4% relative gap (relative difference between the best possible integer solution and the current best integer solution). Therefore, is not possible to guarantee that the best solution found by the algorithm, after two hours of calculation, is a global optimal.

Table IV.6. Results

Index	Value
Total benefit (€)	46.25
Economic benefit (€)	45.39
Total alternative cost (€)	149.40
Total cost of delivery plastic filament (€)	Not considered
Total cost of transport (€)	3.98
Total labor cost of transport (€)	21.47
Total cost of processing (€)	7.31
Total labor cost of processing (€)	28.31
Amortization cost of the machine (€)	42.95
Environmental benefit (€)	0.86
Total cost of emissions by fabrication (€)	0.30
Total cost of emissions by delivery of plastic filament (€)	0.70
Total cost of emissions by recycling (€)	0.09
Total cost of emission by transport (€)	0.05
Amount collected (kg)	8.30
Amount available (kg)	8.30
Number of points available for collection	23
Number of points collected	23
Processing days	5
Number of routes	1
Total distance traveled (km)	26.52
Total motorcycle distance (km)	0
Total car distance (km)	26.52
CO ₂ saving (kg of CO ₂ eq.)	43.12
Relative gap	0.04
Absolute gap	2.05
Best possible	48.30
Resource usage (s)	7200

The total amount of PLA plastic waste to be collected is 8.30 kg per month. This plastic is collected over a total distance of 25.52 km. All this operation enables us to stop emitting 43.12 kg of CO₂ eq., corresponding to a CO₂ eq. reduction of 86.12 % compared with the current situation.

The value of the Economic Benefit is mainly due to the high difference obtained by not buying plastic filament on the market, compared to the costs of collection and recycling, which are very low in comparison. The Environmental Benefit results mainly from no emissions being caused by transporting the plastic filament from the manufacturing point to the recycling point.

The model solution derived shows a number of 1 closed path needed to collect PLA plastic waste from 23 selected schools/high schools out of 23 potential schools/high schools. To perform the collection, the model solution proposes the route shown in [Figure IV.3](#). Only one car is needed to perform the collection using the route shown in [Figure IV.3](#).

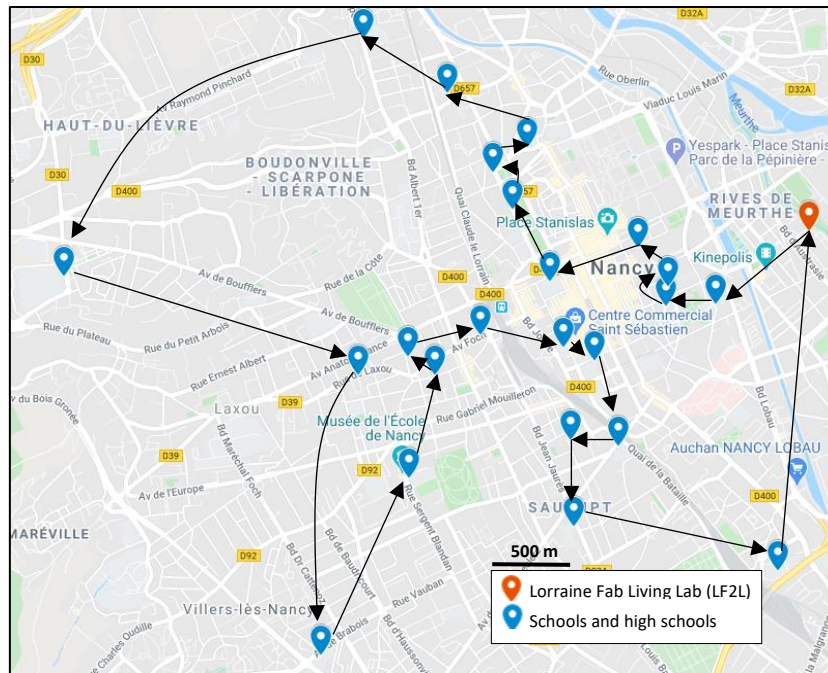


Figure IV.3. Solution map

4.6 Sensitivity analysis

In order to assess how the result changes with respect to the model parameters, a sensitivity analysis was performed with a selected set of parameters in order to analyze results across different scenarios. This enables decision makers to validate the coherence of the model, but also to explore the evolution of potential scenarios of the modeled system. In this case, the influence on the total benefit (economic and environmental) of the following parameters are analyzed: quantity of plastic waste per printer and plastic filament purchasing cost.

4.6.1. Variation of plastic waste per printer quantity

The model was executed repeatedly by varying the amount of PLA waste per printer per month by 0.125 kg to reach 0.729 kg, where it is estimated that the maximum recycling capacity is reached. Then, the amount was varied to reach 1 kg of PLA waste per printer per week. This analysis aims to represent the implication of more intensive future use of 3D printers in secondary schools within the network, leading to higher quantities of plastics to be recycled. This scenario could take place, taking into account the governmental support program applicable in the aforementioned region. The results of the benefits obtained are shown in Fig. IV.4. The details of the results and GAMS output information are presented in Table IV.7.

Looking at the results shown in Fig. IV.4, it can be seen that the Economic Benefit follows the same behavior as the Total Benefit. It is also evident that the increase in Total Benefit is mainly due to the increase in Economic Benefit, where the Environmental Benefit corresponds to the difference between these. The low environmental benefit obtained (monetarily represented), is mainly due to the low

price per Kg of CO₂ eq. considered (€ 20/ton) as well as the low amount of CO₂ eq. due to the scale of the problem (local).

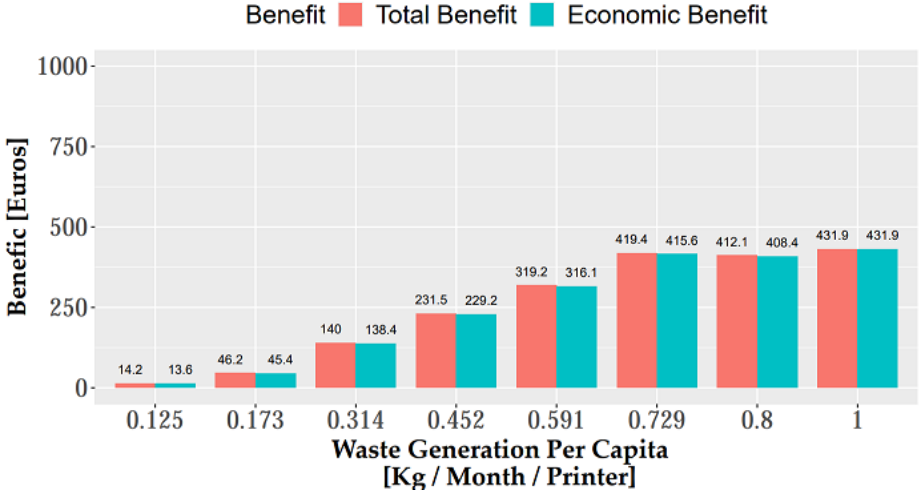


Figure IV.4. Model sensitivity analysis with variation of the quantity of plastic waste per printer

If we consider the Environmental Benefit obtained in terms of amount of reduced CO₂ eq. emissions (Fig. IV.5) reduced, we can see that the amount of saved CO₂ eq. increases until we reach 0.729 kg of PLA waste per printer per week. Thereafter, the amount of CO₂ eq. saved tends to remain constant, or to slightly increase. This occurs because by increasing the amount of PLA waste per printer per week, it is possible to reach the maximum production capacity of the recycling point by collecting waste from the nearest points.

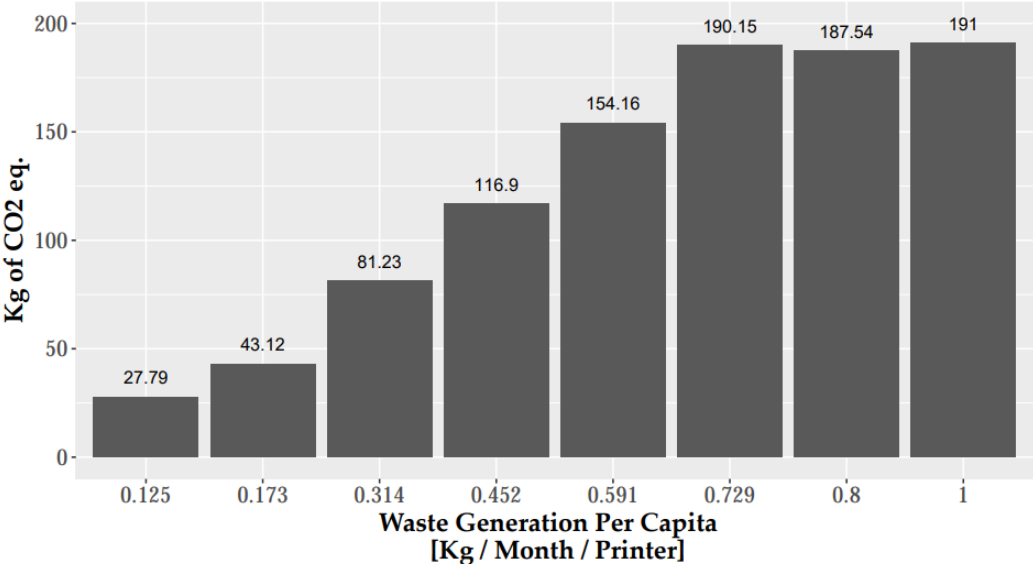


Figure IV.5. CO₂ eq. savings by variation of the quantity of plastic waste per printer

Table IV.7. Results of variation of the plastic waste per printer quantity.

Index	0.125 kg	0.173 kg	0.314 kg	0.452 kg	0.591 kg	0.729 kg	0.8 kg	1 kg
Total Benefit (€)	14.19	46.25	140.04	231.50	319.20	419.42	412.11	431.85
Economic Benefit (€)	13.63	45.39	138.41	229.16	316.12	415.61	408.36	431.85
Total alternative cost (€)	94.45	149.40	271.16	390.33	510.37	629.54	618.89	629.69
Total cost of delivery plastic filament (€)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total cost of transport (€)	2.51	3.98	3.98	3.98	4.69	3.98	3.61	2.06
Total cost of processing (€)	4.62	7.31	13.26	19.09	24.96	30.79	30.27	30.80
Total labor cost of transport (€)	13.53	21.47	21.49	21.47	25.29	21.47	19.46	11.11
Total labor cost of processing (€)	17.21	28.31	51.06	73.69	96.36	114.74	114.24	114.75
Amortization cost of the machine (€)	42.95	42.95	42.95	42.95	42.95	42.95	42.95	42.95
Environmental Benefit (€)	0.56	0.86	1.63	2.34	3.08	3.80	3.75	3.83
Total cost of emissions by fabrication (€)	0.19	0.30	0.54	0.78	1.02	1.26	1.24	1.26
Total cost of emissions by delivery of plastic filament (€)	0.44	0.70	1.28	1.84	2.40	2.96	2.91	2.96
Total cost of emissions by recycling (€)	0.19	0.09	0.16	19.09	0.30	0.36	0.36	0.36
Total cost of emissions by transport (€)	0.06	0.05	0.04	0.05	0.04	0.05	0.04	0.03
CO ₂ saving (kg of CO ₂ eq.)	27.79	43.12	81.23	116.90	154.16	190.15	187.54	191.00
Possible collection points	23.00	23.00	23.00	23.00	23.00	23.00	23.00	23.00
Points selected by the model	20.00	23.00	23.00	23.00	23.00	23.00	20.00	16.00
Amount available (kg)	6.00	8.30	15.07	21.70	28.37	34.99	38.40	48.00
Amount collected (kg)	5.25	8.30	15.07	21.70	28.37	34.99	34.40	35.00
Processing days	3.00	5.00	9.00	13.00	17.00	20.00	20.00	20.00
Number of routes	1.00	1.00	1.00	1.00	2.00	1.00	2.00	1.00
Number of routes of the car	0.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00
Number of routes of the motorcycle	1.00	0.00	1.00	0.00	2.00	0.00	1.00	0.00
Total distance traveled (km)	16.72	26.52	26.55	26.52	31.33	26.52	24.04	13.72
Total motorcycle distance (km)	17.72	0.00	26.55	0.00	31.33	0.00	13.37	0.00
Total car distance (km)	0.00	26.52	0.00	26.52	0.00	26.52	10.67	13.72
Relative gap	0.14	0.04	0.02	0.01	0.02	0.00	0.02	0.01
Absolute gap	2.34	2.05	2.75	1.89	6.79	2.01	7.48	3.52

Considering the economic aspects, operating costs in particular (Fig. IV.6), we can observe that the economic benefit is mainly due to the great variation of the alternative cost (cost of buying virgin plastic in the marketplace) according to the quantity of plastic waste PLA per printer per week. In terms of costs related to recycling (transportation, labor and processing), these do not suffer a great variation in relation to the quantity of PLA plastic waste per printer per week. In addition, the distribution of these is similar in the eight solutions shown below.

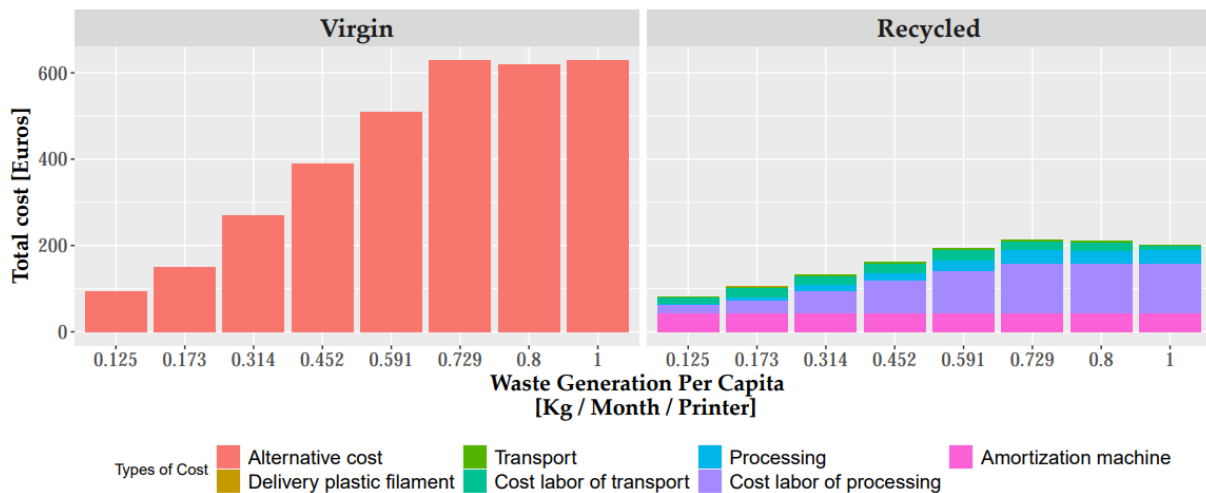


Figure IV.6. Comparison of the total cost between virgin and recycled plastic

4.6.2. Variation of the plastic filament purchasing cost

The purchase price of the virgin plastic filament in the marketplace may change in the future, a factor which directly affects the economic aspect. In particular, we must consider here a price reduction as a consequence of the 3D printing diffusion, leading to higher manufacturing production capacities and economies of scale. As such, in order to perform the sensitivity analysis, the purchase price of the virgin plastic filament used in the case study (19.99 euros per kilogram) was changed and combined with the different solutions obtained, varying the quantity of plastic waste per printer considered in section 4.6.1. The results obtained are shown in Fig. IV.7.

In the first results, we can see that, when considering 0.173 kg of PLA per printer per month to be recycled, there will only be a benefit if the purchase price remains higher than 13.81 euros per kilogram. Therefore, if the quantity of plastic waste per printer changes, we will observe a benefit if the purchase price is greater than 6.29 euros per kilogram. This limit was installed by the Lorraine Fab Living Lab full recycling capacity.

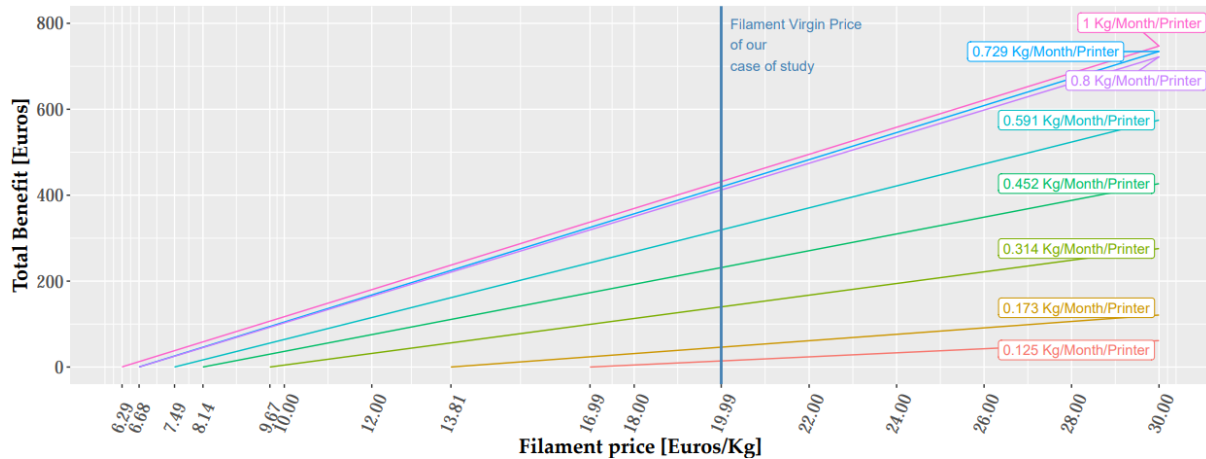


Figure IV.7. Model sensitivity analysis with variation of plastic filament price

4.7 Discussion

Plastic recycling is a pivotal aspect of the Circular Economy strategy for the European Union. This is why, in recent years, there has been an increasing amount of interest in the scientific community and entrepreneurial initiatives to propose solutions to tackle the issue, including the use of plastic recycling for 3D printing purposes. The present review found that most of these studies are concerned with the technical feasibility, proving that it is possible to use this type of material for additive purposes. However, few studies have carried out a holistic analysis of the supply chain network of this distributed plastic recycling approach. This type of analysis is crucial in order to validate its economical sustainability in the long term. With the purpose of evaluating the implementation of a distributed plastic recycling network considering the decision-making process, this study proposed a MILP model in order to assess the economic and environmental feasibility assessment of this recycling approach. The results demonstrate the economical and environmental benefits. From the economic perspective, the necessary monthly benefits are obtained to cover the machine amortization, operational costs and to generate savings reducing the expenses on virgin filaments. From an environmental perspective, it is possible to reduce potentially over 50% the CO₂ eq. emissions compared to the use of virgin plastic filament.

This result also considers a reduced (conservative) volume of plastic waste per printer, which enables us to presume that the real values of waste may be larger. Indeed, the sensitivity analysis carried out from the case study enables us to define the minimum conditions required, according to possible changes in the market (in terms of quantity of PLA plastic waste and virgin filament price) in which the local plastic recycling network in small quantities is feasible. This paper constitutes the first work to assess the logistical feasibility to recycle for open-source 3D printing.

From an industrial/entrepreneurial perspective, this type of analysis represents a step forward in terms of application and/or implementation of this plastic recycling approach, for business purposes. This model could be used in order to make operational decisions in the context of a small plastic recycling company or facility of a company looking to market 3D plastic filament of recycled plastic. The proposed recycling network can also be implemented by public or non-profit entities, due to the low investment required by the OS nature of the various extruder machines. Also, other extended

innovations spaces such as Fab Labs (which currently are more than 1.600 worldwide³²) could possibly replicated the recycling process.

3D printing can be considered as a developing market. In the future, the use of 3D printing and thus the consumption of plastic filament may increase: one cause of this may be the development of distributed manufacturing. The results of the sensitivity analysis show that as the consumption of plastic filament increases, the economic and environmental feasibility of the local plastic recycling network will be possible at decreasing prices of virgin plastic filament. From a market perspective, this implies that as the 3D printing market grows and the price of virgin plastic filament decreases, implementation of this network will increase in effectiveness at ever lower prices. Therefore, under these conditions, the proposed approach could be even more favorable to the distributed recycling approach.

Compared to most sophisticated models in the literature, this model has been developed in a simple way, in order to analyze the economic and environmental benefits of this new approach to plastic recycling before integrating other aspects in the model. Furthermore, the model has been developed for collection and recycling at a single recycling point in order to fit the pre-existing physical system of collecting points and recycling facilities.

Considering that the economic and environmental benefits of this recycling approach has been demonstrated, other aspects can be integrated into a more robust model. From the technical perspective, the lack of mono-streams waste plastic difficult the distributed approach. The identification of relatively clean and homogeneous plastic wastes is an important barrier to overcome by industry, consumers, and institutions. In the social dimension and political context are the main elements to add to a more robust model in order to assess local network feasibility. Considering the social aspects, the uncertainty regarding the amount of plastic waste available and people's behavior regarding this approach of plastic recycling are opportunities to be further explored. Finally, from a political perspective, possible subsidies for this recycling approach or policies to promote the use of plastic recycling can be explored, such as a reduced price if the filament is made of recycled plastic.

4.8 Summary

In this chapter, the economic and environmental benefits of a distributed closed loop supply chain network for plastic recycling using OS 3D printing technologies have been assessed.

A MILP model was proposed and used to support the decision-making process during the feasibility evaluation. This enables decision-makers to select the polymer waste sources from which polymer waste must be collected, the number of collection routes required, the sequence of collection routes, and the means of transport to be used on each route, thus knowing the amount of plastic waste at each point and seeking economic and environmental benefits throughout the recycling operation. The model is applied to the design of a local recycling network demonstrator in the Lorraine region in France.

The results obtained from the application of the model to the case study and its sensitivity analysis suggest replication of this recycling node in different places to form the distributed recycling network.

³² Fablabconnect, "1,600 Fab Labs Worldwide!," 2019. [Online]. Available: <https://www.fablabconnect.com/1600-fab-labs-worldwide/>

However, as shown in the sensitivity analysis, the system depends on other elements determined by the context, such as the demand for 3D printers and the consumption of filament. In the following chapter ([chapter V](#)), the system dynamic model developed to integrate these and other elements into the evaluation is presented.

Chapter V. System level: A system dynamic model for the evaluation of a sustainable distributed plastic recycling network.

5.1. Chapter introduction

In this chapter, the system dynamic model developed for the evaluation of distributed plastic recycling is presented, which corresponds to the upper layer of the proposed analysis and modeling approach. The model developed has been applied to a case study. The results are presented and discussed.

5.2. System Dynamics modelling

In dynamic system modeling, the first step is the creation of a causal diagram [11]–[13]. The main goal of a causal diagram is to (1) identify the main variable in the system according to the problem specified, and (2) to show the relationships between the elements considered in the system. Figure V.1 shows an example to model the behavior of the population considering birth and mortality. In the figure, a direct relationship between the birth rate and the population can be observed, that is, an increase in the birth rate causes an increase in the population. On the other hand, the relationship between the death rate and the population is inverse, i.e. an increase in the death rate causes a decrease in the population. After identifying all the relationships between the elements, it is necessary to identify and classify the loops generated. There are two types of loops: (1) positive (reinforcing) loops and (2) negative (balancing) loops. Reinforcing loops are those in which a change in the variable results in the same effect on it. On the other hand, balancing loops are those in which a change in the variable has the opposite effect on it.

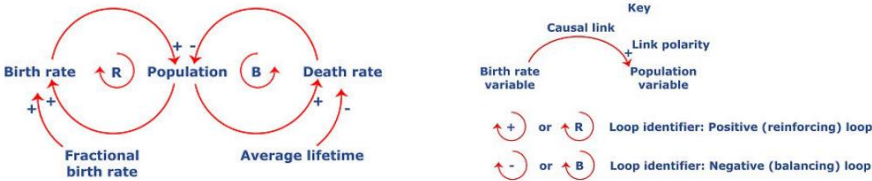


Figure V.1. Example of causal diagram³³

The second step corresponds to the construction of the stock and flow diagram. The stock and flow diagram represents the accumulation (stock) of the variables, which varies according to their flows (rates) over time. Figure V.2 shows how the elements are represented in a stock and flow diagram. The stock is represented by rectangles. Flows are represented by pipes, which go in or out depending on whether it is an incoming or outgoing flow. Control valves the flows, and clouds represent the sources and sinks for the flows. In addition, circles are used to represent auxiliary variables, and arrows are used to connect the variables [13]. Considering the causal diagram shown in Figure V.1, the population would correspond to a stock, and the birth and death rates would correspond to the inflows and

³³ J. Sussman, "Introduction to Engineering Systems, ESD.00 System Dynamics," *Business*, 2012.

outflows respectively. Fractional birthrate and average lifetime would correspond to auxiliary variables.

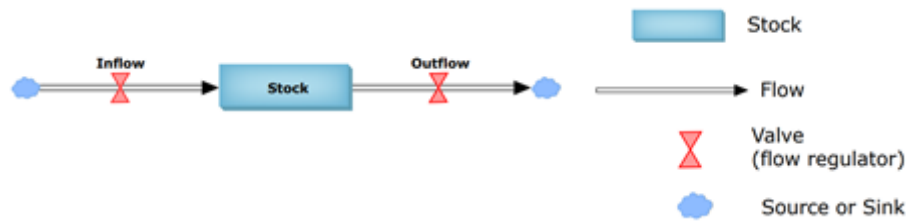


Figure V.2. Stock and flow diagram representation³⁴

Finally, the model developed must be validated. For this purpose, the literature proposes 12 validation tests [13]: Boundary adequacy, Structure Assessment, Dimensional Consistency, Parameter Assessment, Extreme Conditions, Integration Error, Behavior Reproduction, Behavior Anomaly, Family Member, Surprise Behavior, Sensitivity Analysis and System Improvement. Each validation test will be explained in the model validation section.

In the following sections the description of the model is made.

5.3. Description of the system to be modelled

5.3.1. Purpose of the model

The objective of the model is to determine the conditions under which distributed plastic recycling for 3D printing can be developed at a local scale.

By conditions, we meant the following sub questions:

- What is the dynamic of the economical profit in function of the recycling cost, operational cost and available wastes in a local area?
- What are the environmental gains under the hypothesis of deployment a local circuit recycling hub?
- What are the social gains under the hypothesis of deployment a local circuit recycling hub?

In the context of distributed plastic recycling, a fundamental aspect to consider is the behavior of the 3D printing market. This market influences the number of printers to be supplied with recycled filament (demand), another aspect to be considered in the system. As there is a demand, there must be a supply, which would correspond, in our case, to the distributed plastic recycling. Specifically, the number of recycling facilities to be implemented must be considered. Finally, the availability of waste (source of the system) and the processing capacity of the system must be considered. In conclusion, it is possible to identify 5 subsystems (see Figure V.3) which interact with each other in the context of distributed plastic recycling using 3D printing technology. These subsystems correspond to: (1) 3D printing market, (2) 3D plastic recycled filament market, (3) Implementation of smalls hubs of plastic recycling, (4) Waste generation and (5) recycling chain capacity. Each subsystem is described below.

³⁴ A. Siddiqi, "Introduction to Engineering Systems, ESD.00 System Dynamics."

- **Recycling chain capacity:** In this subsystem, the collection and recycling capacity of the network is modelled, which depends on the number of available recycling points and the capacity of the recycling chain (the set of machines). In this subsystem, the recyclability of the collected plastic waste (which depends on the quality or level of degradation of the plastic waste) must be considered.
- **Outputs:** Knowing that a greater number of criteria are necessary to consider all the challenges in the plastics processing industry, partially, as evaluation criteria for the distributed plastic recycling system from the point of view of sustainability, the following criteria are partially proposed. As economic criteria, the economic benefit (profit) of the network is considered. As environmental criteria, the CO₂ emissions and the amount of plastic waste recycled are measured. Finally, as social criteria, job creation and the social cost of carbon avoided are considered. The technological and political dimensions are considered through elements within the model.

In the context of distributed plastic recycling for 3D printing, it is possible to identify two types of users and two types of suppliers of recycled plastic filament. On the side of the 3D printing users, it is possible to identify particular users and institutional users. As particular users are considered those people who use 3D printing at home. On the other hand, institutional users are those organizations that use 3D printing for educational purposes (schools, high schools, universities) or for business purposes. As suppliers of recycled plastic filament, we identify two different types of suppliers, first, institutions with profit purposes (considering plastic recycling for 3D printing as a business) and non-profit institutions (that do not consider plastic recycling as a business). Considering the above, as system boundaries, two types of actors have been considered. On the side of the 3D printing users, educational institutions such as high schools, schools and universities have been considered. On the other hand, as recycled plastic filament suppliers, only non-profit institutions have been considered. Finally, one kilogram of plastic filament (virgin or recycled) usable in 3D printing has been considered as the functional unit of the system.

5.4. Presentation of Causal Loop Diagram

To construct the causal diagram of the system, first, causal diagrams have been developed for each subsystem described in the previous section. Then, the causal diagrams obtained for each subsystem have been integrated into a single causal diagram.

5.4.1. Causal diagrams of subsystems

In this section, the causal model for each subsystem will be described as follows.

5.4.1.1 3D printing Market

Figure V.4 shows the causal diagram established for the first subsystem: 3D printing market. In the figure, it can be seen that the number of 3D printers in a particular territory under study depends on the demand for 3D printers within its physical boundaries. The demand for 3D printers affects the demand for filament, either recycled or virgin filament. It is worth mentioning that the demand for printers may have associated causes, such as the development of 3D printing, the price of the 3D printer or even public policies promoting the use of this technology. However, these last were not considered in this model.

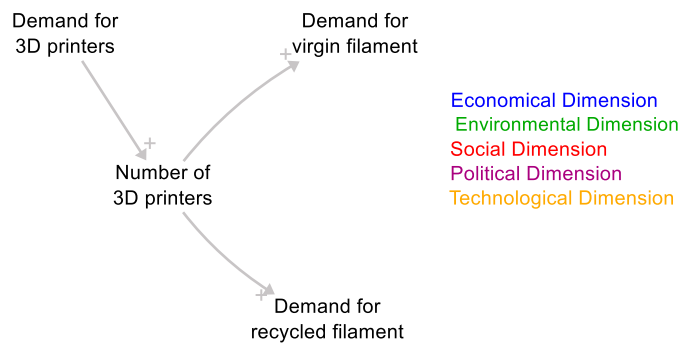


Figure V.4. Causal loop for 3D printing market subsystem

5.4.1.2 3D plastic recycled filament market

As can be seen in Figure V.5, it has been established that the demand for virgin and recycled filament depends on the number of 3D printers in the territory, the consumption of filament per 3D printer, the performance of recycled vs virgin filament and the price of both types of filament. In turn, the demand for each filament affects the amount of sales of each of them. Since the system modeled is limited to recycled filament, sales of this filament also depend on the existing supply or stock of this product. The available stock of recycled filament depends on the amount of filament fabricated by the network in a period of time. Finally, the amount of recycled filament fabricated by the network depends on the fabrication capacity of the network (depending on the number of facilities, the recycling capacity of the extruder and granulator implemented in each facility, and the storage capacity of each facility) and the amount of plastic waste available to be recycled.

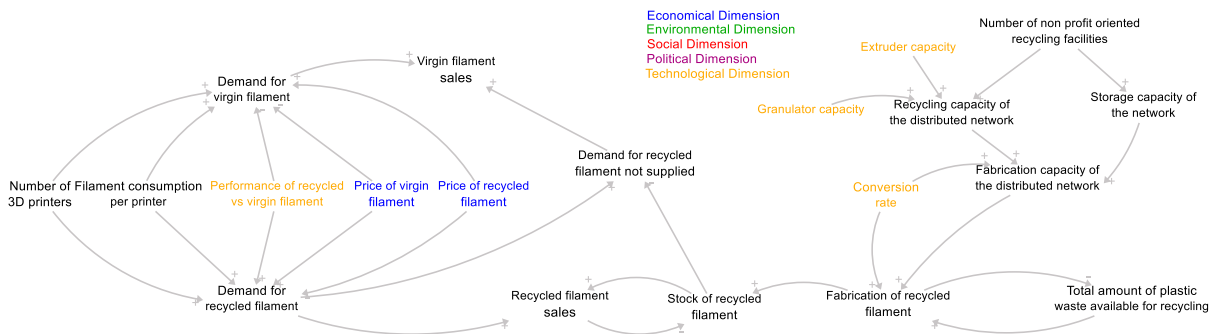


Figure V.5. Causal loop for 3D plastic filament market

5.4.1.3 Implementation of smalls hubs of plastic recycling

As can be seen in Figure V.6, the implementation of new non-profit facilities depends on the necessary investment, the profit obtained from the sale of recycled filament, the difference between the demand for recycled filament and the fabrication capacity of the network, and the availability of plastic waste (plastic waste that cannot be collected). Different factors would motivate the implementation of new non-profit recycling facilities: a higher profit from the sale of recycled filament under the conditions of a lower investment, a high amount of not collected plastic waste, a difference between demand and fabrication capacity of the system. On the one hand, profit is determined by the costs of the recycling activity (collection, recycling, labor and inventory). On the other hand, the price of the extruder and granulator, the cost of the vehicle to be used for collection and the investment subsidy determine the initial investment needed.

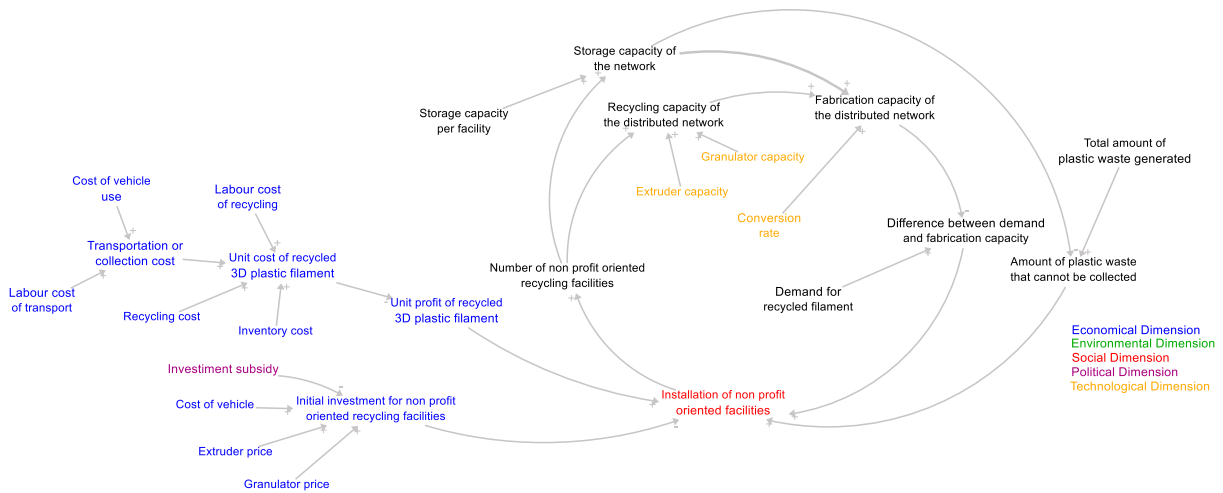


Figure V.6. Causal loop of Implementation of small's hubs of plastic recycling subsystem

5.4.1.4 Waste generation and Recycling chain capacity

Figure V.7 presents simultaneously the diagram obtained for the subsystems waste generation and recycling chain capacity. As can be observed, in Fig.V.7 two types of plastic waste have been considered: (1) virgin 3D plastic waste and (2) recycled 3D plastic waste. These correspond to the plastic waste to be collected by the network, which is determined by the storage capacity of the network. The storage capacity is determined by the number of facilities implemented with a given storage capacity. The amount of plastic waste to be collected depends on the amount of waste available for collection and the storage available, in which the plastic waste available for recycling and the recycled plastic filament in stock are considered. One of the main assumptions in the model is that the domestic plastic waste has not been considered due to the complex treatment (sorting, cleaning, and decontamination) of this waste during recycling.

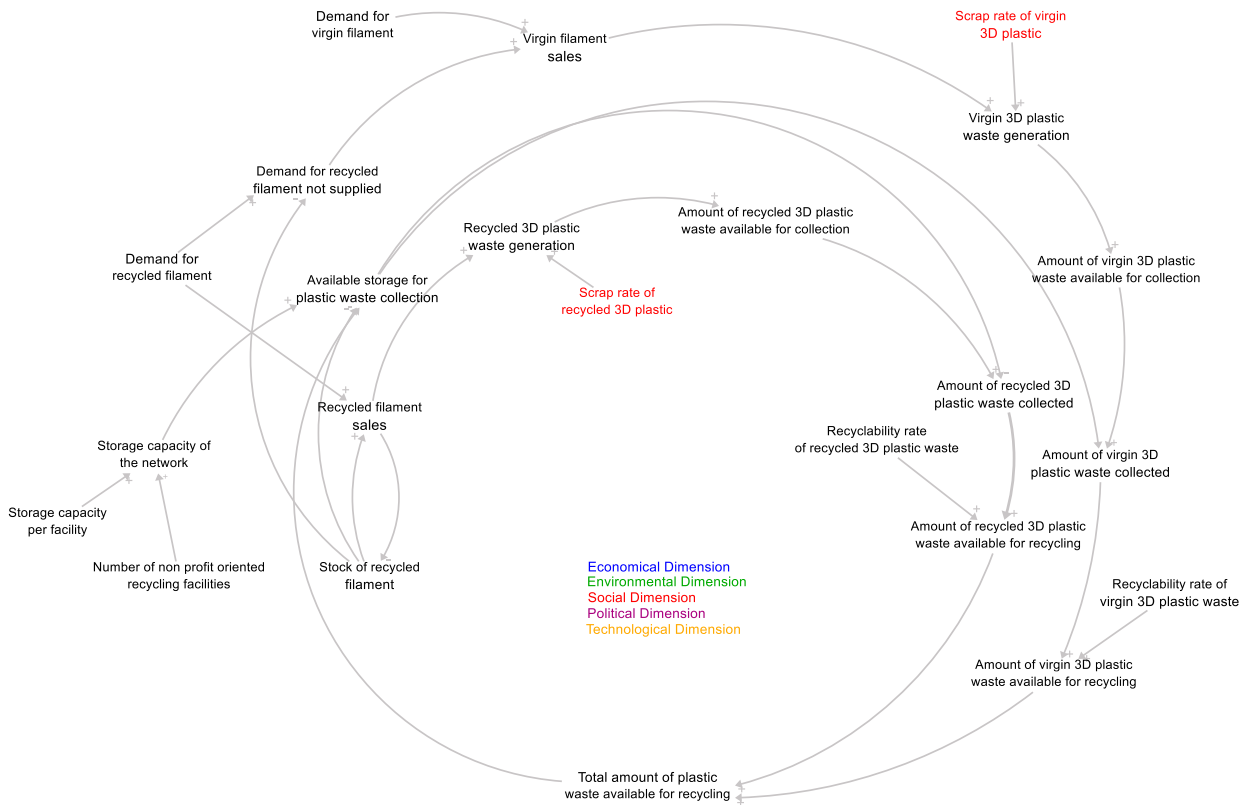


Figure V.7. Causal loop of Waste generation and Recycling chain capacity subsystems

5.4.1.5 Outputs

The outputs presented in the [Figure V.8](#) of the model are divided in three main aspects: (1) Economical, (2) Environmental and 3) Social.

First, from the economical dimension, the global profit is considered, which is a function of the sales of recycled filament and the implementation of new recycling facilities. From the environmental perspective, the amount of recycled plastic waste and the amount of not emitted CO₂ eq. (saved) is determined by the sales of recycled filament and the number of routes required for collection. From the social perspective, the job creation is determined by the amount of recycled filament fabricated in a period of time and the number of routes required for collection. Finally, the social cost of carbon avoided (social benefit) is determined by the amount of CO₂ eq. not emitted.

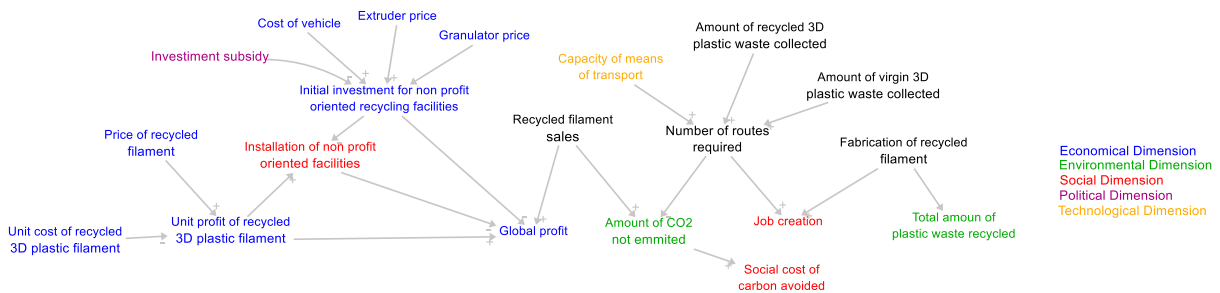


Figure V.8. Causal loop of outputs

5.4.2 Integrated Causal loop diagram

Figure IV.9. represents the causal loop diagram integrating each sub-system explained beforehand. One of the main aspects to highlight of the system is the apparition of twelve balancing loops against three reinforcing loops. A reinforcing loop, corresponds to those causal cycles in which a change in a variable causes a positive feedback in the same variable (due to its interaction with the other elements of the system) [13]. On the other hand, a balancing loop corresponds to those causal cycles in which a change in a variable causes a negative feedback (control) in the same variable [13]. This structural aspect of the systems is based, on the one hand, on mass flow control loops (plastic waste, recyclable plastic waste and recycled filament obtained). On the other hand, it is also possible to observe control loops for the implementation of recycling facilities, which are controlled according to the collection and fabrication capacity of the existing facilities. Finally, the demand of each material (recycled and virgin filament), which depend on the demand of printers and filament consumption, are considered as system inputs.

5.4.3 Reinforcing and Balancing loops

As result of the integration of the subsystems, twelve balancing loops and three reinforcing loops have been identified. Each of them is explained below.

In order to present in a better way, the obtained loops, they have been divided into 6 types:

1. Loops based on facilities implementation (7 loops)
2. Loops based available storage for collection (4 loops)
3. Stock control loops (2 loops)
4. Loops based on filament sales and waste generation (2 loops)

Each is explained below.

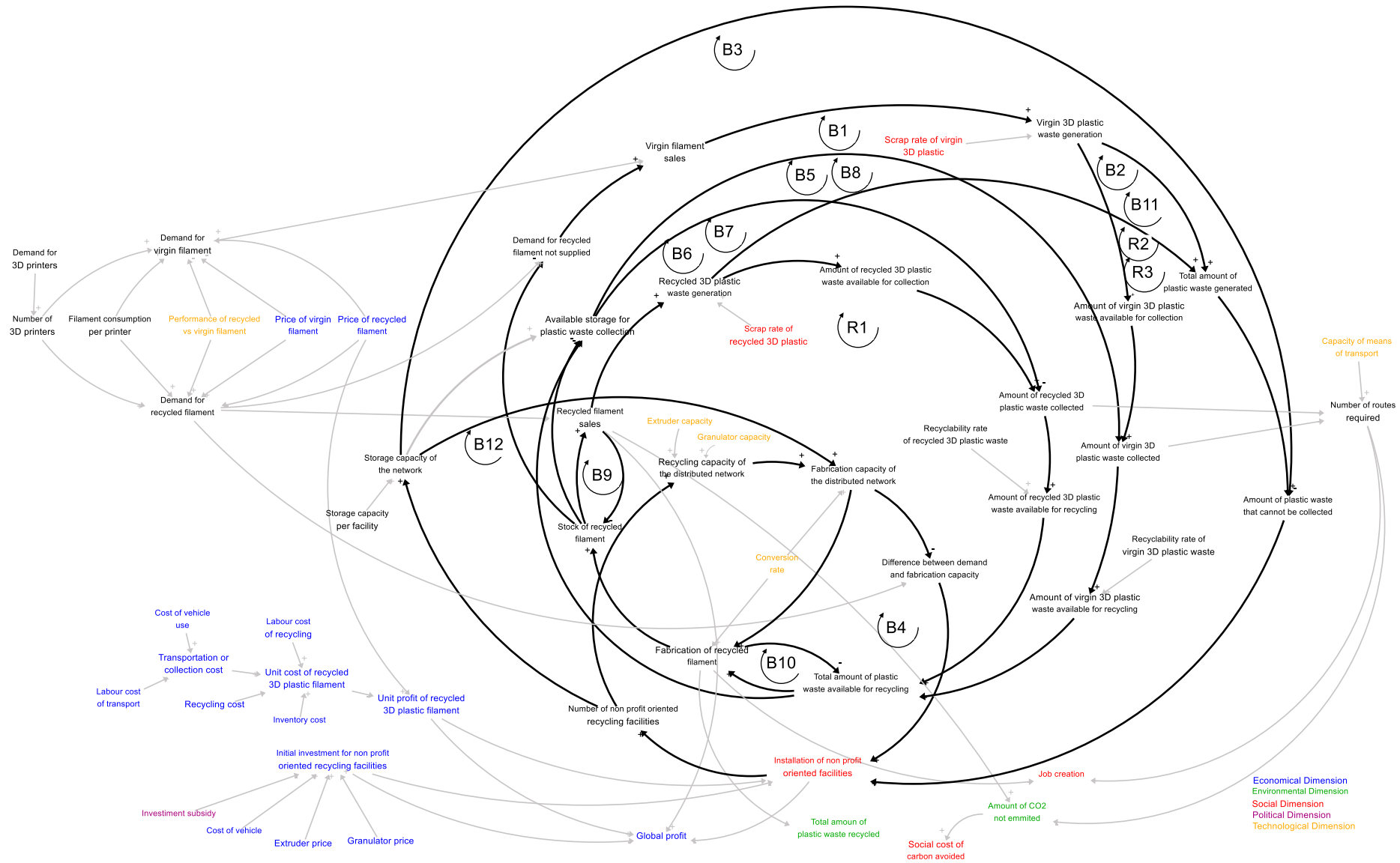


Figure V.9. Causal loop diagram for distributed plastic recycling

5.4.3.1 Loops based on facilities implementation

Figure V.10 presents the loops identified for this group. These loops represent the effects of implementing a new facility or facilities. The implementation of a new installation causes an increase in the number of facilities in the network. The increase in the number of facilities has different effects. On the one hand, an increase in the number of installations causes an increase in the storage capacity of the network. More storage allows less waste to go uncollected (which was one of the reasons for the implementation of a facility). Finally, a lower amount of uncollected waste discourages the implementation of a new facility, leaving the loop controlled (loop B3). Another effect of the implementation of a new facility is an increase in the fabrication capacity of the network, which is enhanced by an increase in the storage capacity and the recycling capacity of the network. An increase in fabrication capacity means that more filament can be fabricated (if there is a sufficient amount of plastic waste available to do so). An increase in the amount of filament fabricated causes an increase in the available stock of recycled filament, which causes different effects depending on the material. In the case of recycled filament, an increase in the stock of recycled filament causes an increase in sales (if the stock is less than the demand for recycled filament). An increase in sales of recycled filament causes an increase in the amount of recycled waste generated, which causes an increase in the amount of plastic waste generated. Finally, this causes a greater amount of waste not to be collected due to the capacity of the network, which motivates the implementation of new facilities. These causes are represented by loops R2 and R3, depending on whether an increase in fabrication capacity due to storage or recycling capacity is considered. On the other hand, the effects caused by R2 and R3 loops are controlled by the effect of recycled filament stock on virgin filament sales. An increase in recycled filament stock (due to the same causes of R2 and R3 loops) causes a decrease in the demand for recycled filament not supplied, which causes a decrease in virgin filament sales. A decrease in sales of virgin filament causes a decrease in the amount of virgin plastic waste generated, which causes a decrease in the total amount of plastic waste generated. Thus, the positive effects of loops R2 and R3 are controlled by loops B2 and B11 (for an increase in manufacturing capacity due to an increase in storage capacity and recycling capacity respectively). Finally, a final effect of the implementation of a new facility is the reduction of the difference between demand and fabrication capacity, which discourages the implementation of new facilities (because the demand can already be fully or almost fully covered by the network). The decrease in the difference between demand and fabrication capacity is due to the increase in storage capacity (B12) and recycling capacity (B4) as a result of the new installation, which causes an increase in fabrication capacity of the network.

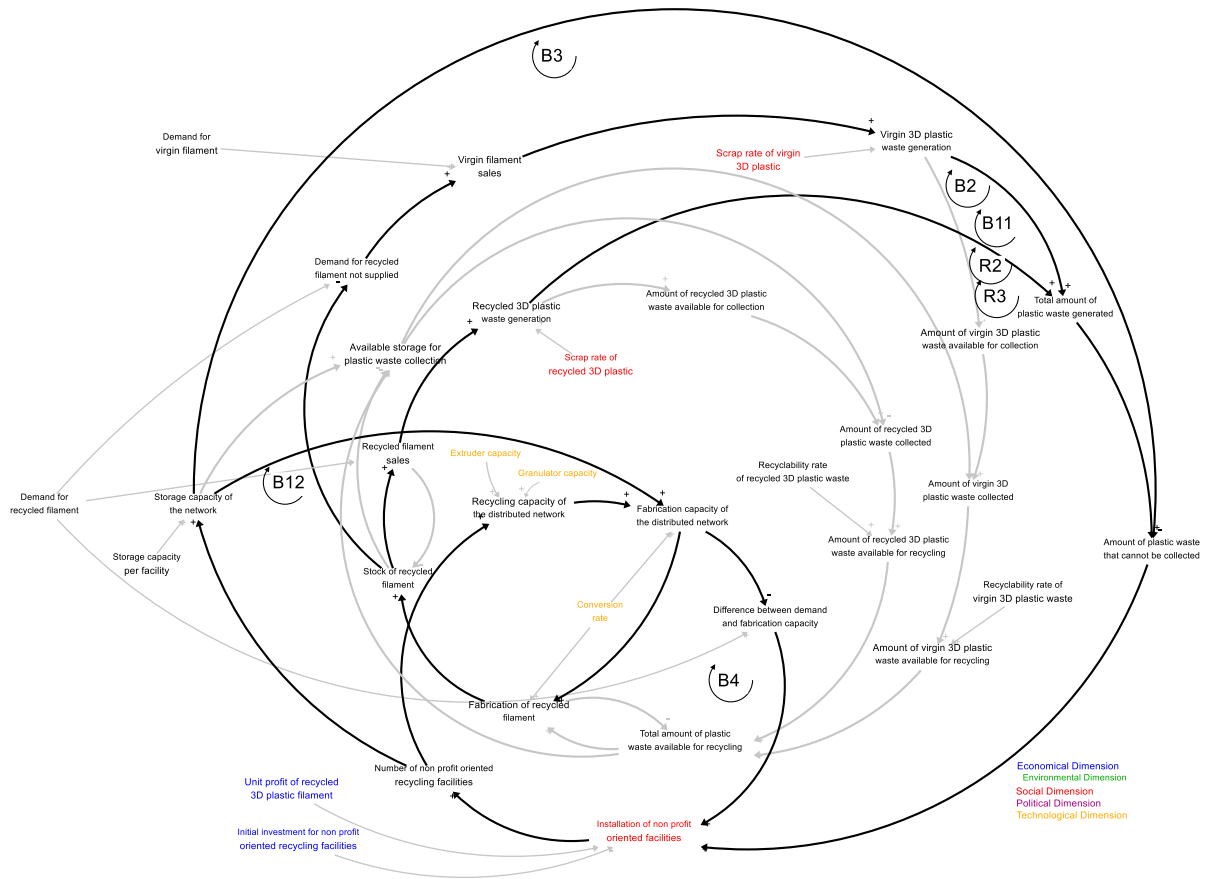


Figure V.10. Loops based on facilities implementation

5.4.3.2 Loops based on available storage for collection

Figure IV.11 presents the loops identified for this group. These loops control the amount collected depending on the available storage. An increase in available storage causes an increase in the amount of plastic waste collected (recycled or virgin) if the amount of waste to be collected is greater. An increase in the amount of waste collected causes an increase in the amount of waste available for recycling, which finally causes a decrease in the available storage. This decrease in available storage can be due to an increase in plastic waste storage or an increase in recycled filament storage (if recycled plastic filament is fabricated using the stored plastic waste). These causes are reflected in loops B6 and B7 for the collection of recycled plastic waste, and in loops B5 and B8 for the collection of virgin plastic waste.

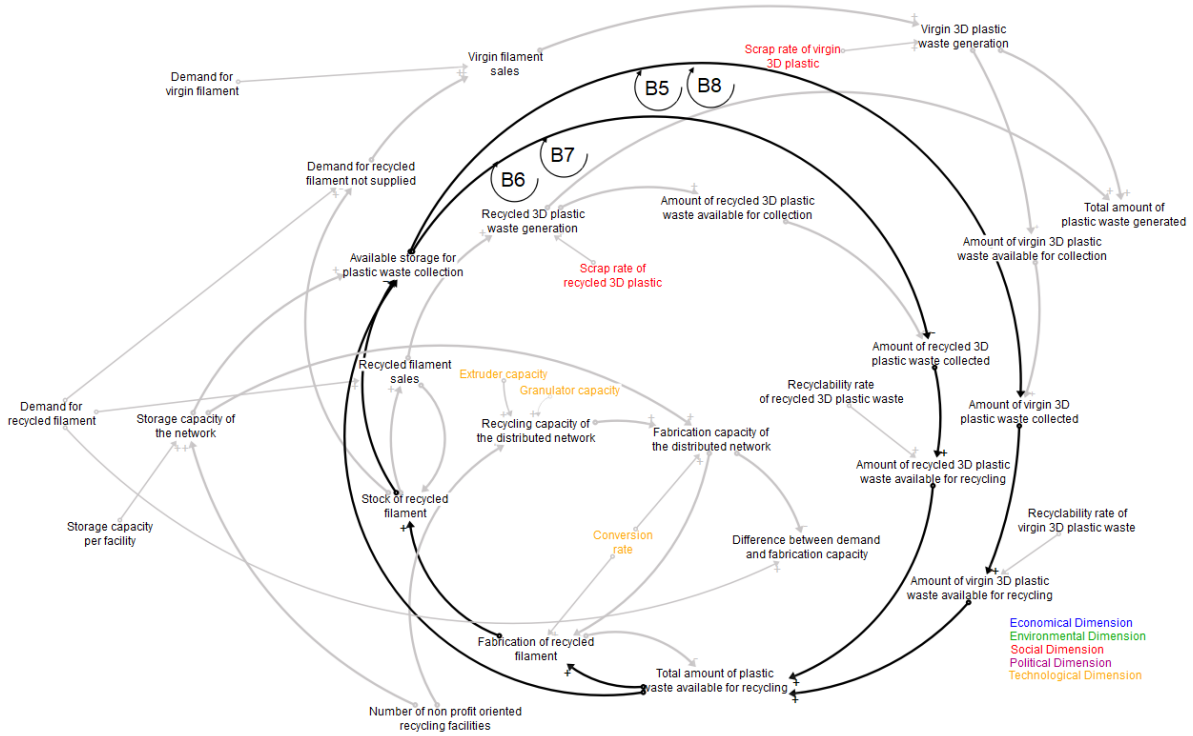


Figure V.11. Loops based on available storage for collection

5.4.3.3 Stock control loops

Figure IV.12 presents the loops identified for this group. These loops control the flow of material. For example, an increase in the stock of recycled filament causes an increase in sales (if the demand is greater than the stock). As a cause of sales, the stock of recycled filament decreases. This effect is represented in loop B9. On the other hand, the B10 loop represents the use of plastic waste for fabrication. As more plastic waste is available for recycling, more filament can be fabricated, which results in a decrease in the amount of plastic waste available due to its use to fabricate the recycled filament.

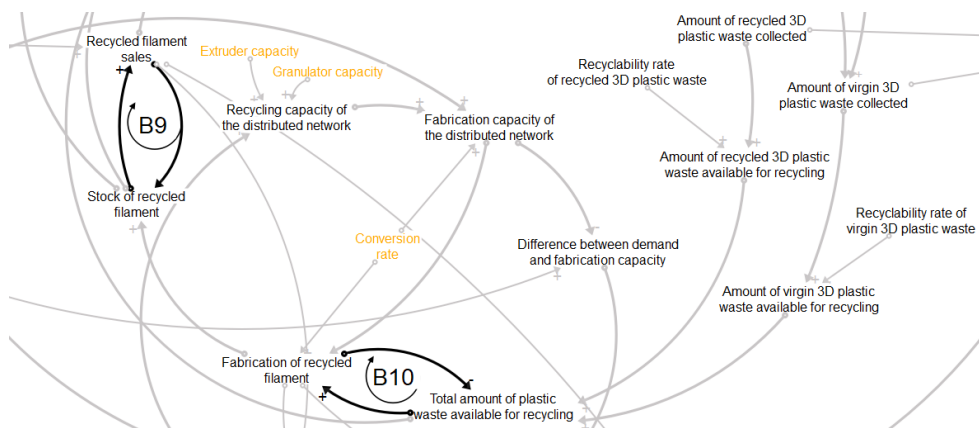


Figure V.12. Stock control loops

5.4.3.4 Loops based on filament sales and waste generation

Figure IV.13 presents the loops identified for this group. These loops represent the relationship between the use of waste for fabrication of recycled filament and the generation of plastic waste. An increase in the amount of plastic waste available for recycling causes an increase in the fabrication of recycled filament, which causes an increase in the stock of recycled filament. This increase in stock has different effects depending on the material. On the one hand, in the case of recycled filament, an increase in its stock causes an increase in sales (if the demand is greater than the stock). An increase in sales of recycled filament causes an increase in waste generated from this material, which results in an increase in the amount of waste available for recycling. On the other hand, in the case of virgin filament, an increase in the stock of recycled filament causes a decrease in sales of this filament (due to a decrease in the demand for recycled filament not supplied). A decrease in sales of virgin filament causes a decrease in waste generated and collected from this material, which results in a decrease in the amount of waste available for recycling. In conclusion, the effects on recycled filament are controlled by the effects on virgin filament. It should also be noted that the variables of recycled filament stock and quantity of available plastic waste are controlled by the balance loops B9 and B10 described in the previous section (stock control loops).

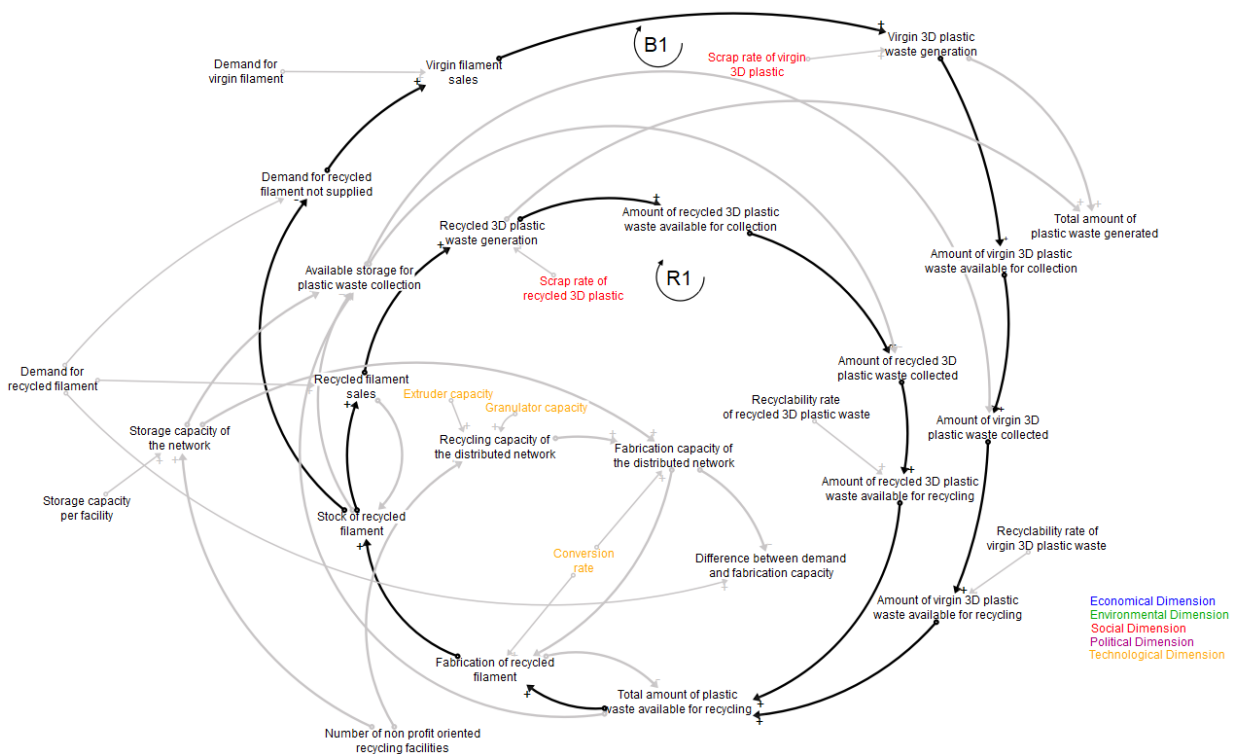


Figure V.13. Loops based on filament sales and waste generation

5.5. Presentation of Stock and Flow diagram

Figure V.14 presents the stock and flow diagram obtained for the distributed plastic recycling. The model equations are presented in Table V.1. The assumptions established for the construction of the model are presented in Table V.2.

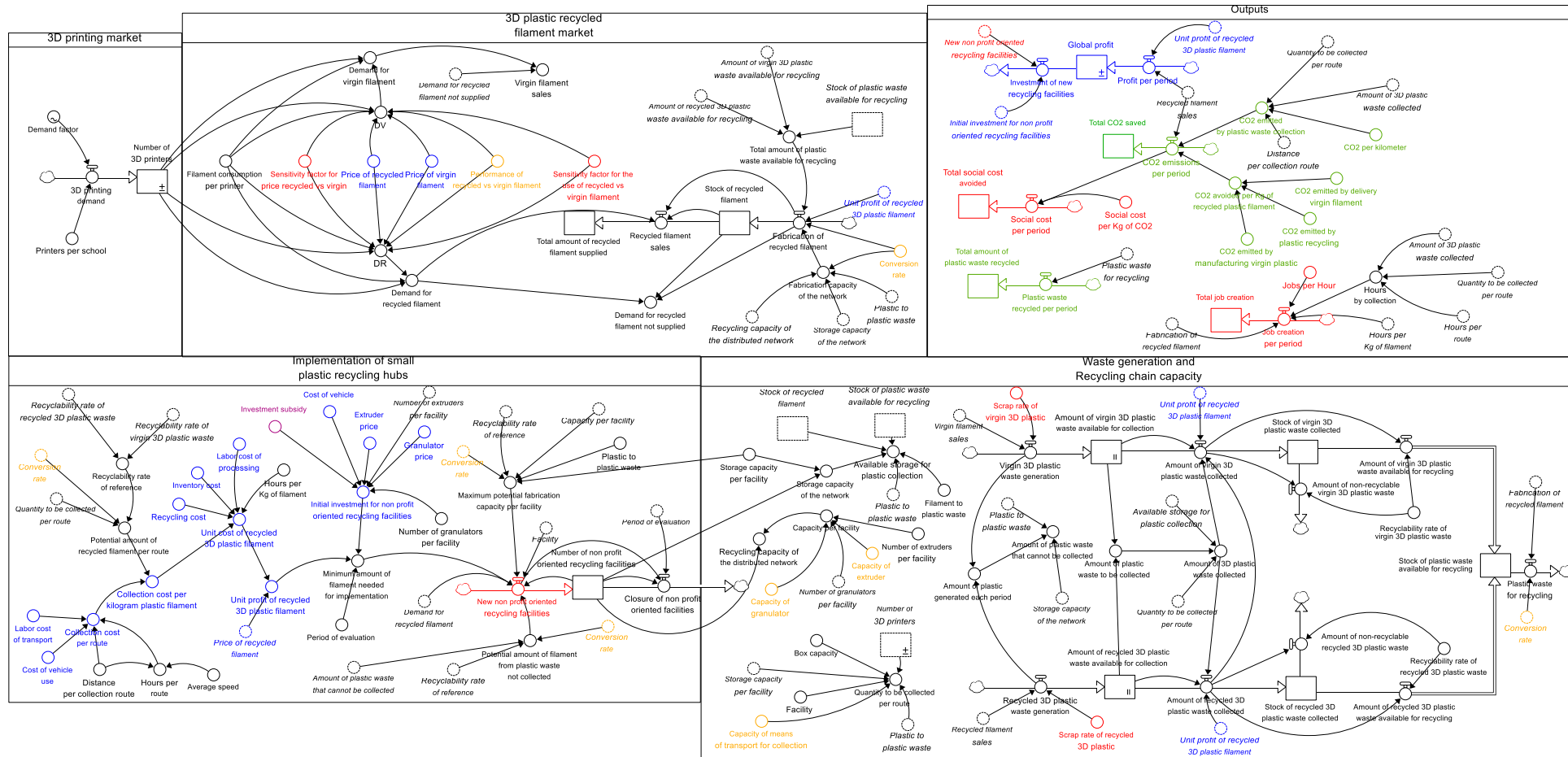


Figure V.14. Stock and Flow diagram for distributed plastic recycling.

Blue= economic dimension, green= environmental dimension, red= social dimension, orange= technological dimension, purple= political dimension.

Table V.1 Model equations

Variable	Type	Equation	Unit
Amount of recycled 3D plastic waste available for collection(t)	Endogenous	Amount of recycled 3D plastic waste available for collection (t - dt) + (Recycled 3D plastic waste generation - Amount of recycled 3D plastic waste collected) * dt INIT Amount of recycled 3D plastic waste available for collection = Constant	Kg of plastic waste
Amount of virgin 3D plastic waste available for collection(t)	Endogenous	Amount of virgin 3D plastic waste available for collection (t - dt) + (Virgin 3D plastic waste generation - Amount of virgin 3D plastic waste collected) * dt INIT Amount of virgin 3D plastic waste available for collection = Constant	Kg of plastic waste
Global profit(t)	Endogenous	Global profit (t - dt) + (Profit per period - Investment of new recycling facilities) * dt INIT Global profit = -Initial investment for non profit oriented recycling facilities*Number of non profit oriented recycling facilities	Euros
Number of 3D printers(t)	Endogenous	Number of 3D printers (t - dt) + (3D printing demand) * dt INIT Number of 3D printers = Constant	Printer
Number of non profit oriented recycling facilities(t)	Endogenous	Number of non profit oriented recycling facilities (t - dt) + (New non profit oriented recycling facilities - Closure of non profit oriented facilities) * dt INIT Number of non profit oriented recycling facilities=Constant	facility
Stock of plastic waste available for recycling(t)	Endogenous	Stock of plastic waste available for recycling (t - dt) + (Amount of virgin 3D plastic waste available for recycling + Amount of recycled 3D plastic waste available for recycling - Plastic waste for recycling) * dt INIT Stock of plastic waste available for recycling = Constant	Kg of plastic waste
Stock of recycled 3D plastic waste collected(t)	Endogenous	Stock of recycled 3D plastic waste collected (t - dt) + (Amount of recycled 3D plastic waste collected - Amount of recycled 3D plastic waste available for recycling - Amount of non-recyclable recycled 3D plastic waste) * dt INIT Stock of recycled 3D plastic waste collected= Constant	Kg of plastic waste
Stock of recycled filament(t)	Endogenous	Stock of recycled filament (t - dt) + (Fabrication of recycled filament - Recycled filament sales) * dt INIT Stock of recycled filament = Constant	Kg of filament
Stock of virgin 3D plastic waste collected(t)	Endogenous	Stock of virgin 3D plastic waste collected (t - dt) + (Amount of virgin 3D plastic waste collected - Amount of virgin 3D plastic waste available for recycling - Amount of non-recyclable virgin 3D plastic waste) * dt INIT Stock of virgin 3D plastic waste collected = Constant	Kg of plastic waste
Total amount of plastic waste recycled(t)	Endogenous	Total amount of plastic waste recycled (t - dt) + (Plastic waste recycled per period) * dt INIT Total amount of plastic waste recycled=Constant	Kg of plastic waste
Total amount of recycled filament supplied(t)	Endogenous	Total amount of recycled filament supplied (t - dt) + (Recycled filament sales) * dt INIT Total amount of recycled filament supplied=Constant	Kg of filament
Total CO2 saved(t)	Endogenous	Total CO2 saved (t - dt) + (CO2 emissions per period) * dt INIT Total CO2 saved=Constant	Kg of CO2 eq.
Total job creation(t)	Endogenous	Total job creation (t - dt) + (Job creation per period) * dt INIT Total job creation= Constant	Jobs
Total social cost avoided(t)	Endogenous	Total social cost avoided (t - dt) + (Social cost per period) * dt INIT Total social cost avoided= Constant	Euros
3D printing demand	Exogenous	Demand factor*Printers per school	Printer/Months
Amount of non-recyclable recycled 3D plastic waste	Endogenous	Amount of recycled 3D plastic waste collected*(1-Recyclability rate of recycled 3D plastic waste)	Kg of plastic waste / Months
Amount of non-recyclable virgin 3D plastic waste	Endogenous	Amount of virgin 3D plastic waste collected*(1-Recyclability rate of virgin 3D plastic waste)	Kg of plastic waste / Months
Amount of recycled 3D plastic waste available for recycling	Endogenous	Amount of recycled 3D plastic waste collected*Recyclability rate of recycled 3D plastic waste	Kg of plastic waste / Months

Table V.1 Model equations (Continuation)

Variable	Type	Equation	Unit
Amount of recycled 3D plastic waste collected	Endogenous	IF (Unit profit of recycled 3D plastic filament \geq 0) THEN (MIN(Amount of recycled 3D plastic waste available for collection/DT; Amount of 3D plastic waste collected/DT)) ELSE (0)	Kg of plastic waste / Months
Amount of virgin 3D plastic waste available for recycling	Endogenous	Amount of virgin 3D plastic waste collected*Recyclability rate of virgin 3D plastic waste	Kg of plastic waste / Months
Amount of virgin 3D plastic waste collected	Endogenous	IF (Unit profit of recycled 3D plastic filament \geq 0) THEN (MIN(Amount of virgin 3D plastic waste available for collection/DT; ((Amount of 3D plastic waste collected/DT)-Amount of recycled 3D plastic waste collected))) ELSE (0)	Kg of plastic waste / Months
Closure of non profit oriented facilities	Endogenous	PULSE(INIT (Number of non profit oriented recycling facilities); Period of evaluation; 0)+DELAY(New non profit oriented recycling facilities; Period of evaluation)	facility/Months
CO2 emissions per period	Endogenous	(Recycled filament sales*CO2 avoided per Kg of recycled plastic filament)-CO2 emitted by plastic waste collection	Kg of CO2 eq. / Months
Fabrication of recycled filament	Endogenous	IF (Unit profit of recycled 3D plastic filament \geq 0) THEN (IF (Fabrication capacity of the network \geq Total amount of plastic waste available for recycling*Conversion rate) THEN (Conversion rate*Total amount of plastic waste available for recycling) ELSE (Fabrication capacity of the network)) ELSE (0)	Kg of filament / Months
Investment of new recycling facilities	Endogenous	New non profit oriented recycling facilities*Initial investment for non profit oriented recycling facilities	Euros/Months
Job creation per period	Endogenous	((Fabrication of recycled filament*Hours per Kg of filament)+Hours by collection)*Jobs per Hour	Jobs/Months
New non profit oriented recycling facilities	Endogenous	IF ((Minimum amount of filament needed for implementation \geq 0) AND (Demand for recycled filament-(Maximum potential fabrication capacity per facility*Number of non profit oriented recycling facilities))>(Minimum amount of filament needed for implementation*Facility) AND Potential amount of filament from plastic waste not collected > (Minimum amount of filament needed for implementation*Facility)) THEN (INT(((MIN(Potential amount of filament from plastic waste not collected ; Demand for recycled filament - (Maximum potential fabrication capacity per facility*Number of non profit oriented recycling facilities))) /Maximum potential fabrication capacity per facility)) +1) /DT ELSE (0)	facility/Months
Plastic waste for recycling	Endogenous	Fabrication of recycled filament/Conversion rate	Kg of plastic waste / Months
Plastic waste recycled per period	Endogenous	Plastic waste for recycling	Kg of plastic waste / Months
Profit per period	Endogenous	(Recycled filament sales*Unit profit of recycled 3D plastic filament)	Euros/Months
Recycled 3D plastic waste generation	Endogenous	Scrap rate of recycled 3D plastic*Recycled filament sales	Kg of plastic waste / Months
Recycled filament sales	Endogenous	IF (((Stock of recycled filament/DT)+Fabrication of recycled filament)>Demand for recycled filament) THEN (Demand for recycled filament) ELSE (((Stock of recycled filament/DT)+Fabrication of recycled filament))	Kg of filament / Months
Social cost per period	Endogenous	CO2 emissions per period*Social cost per Kg of CO2	Euros/Months
Virgin 3D plastic waste generation	Endogenous	Virgin filament sales*Scrap rate of virgin 3D plastic	Kg of plastic waste / Months
Amount of 3D plastic waste collected	Endogenous	IF (MIN(Amount of plastic waste to be collected; Available storage for plastic collection) \geq Quantity to be collected per route) THEN (INT(((MIN(Amount of plastic waste to be collected; Available storage for plastic collection)/Quantity to be collected per route))*Quantity to be collected per route) ELSE 0	Kg of plastic waste
Amount of plastic generated each period	Endogenous	Recycled 3D plastic waste generation + Virgin 3D plastic waste generation	Kg of plastic waste/Months
Amount of plastic waste that cannot be collected	Endogenous	(Amount of plastic generated each period*DT) - (Storage capacity of the network*plastic to plastic waste)	Kg of plastic waste
Amount of plastic waste to be collected	Endogenous	Amount of recycled 3D plastic waste available for collection + Amount of virgin 3D plastic waste available for collection	Kg of plastic waste
Average speed	Exogenous	Constant	Km/Hour
Box capacity	Exogenous	Constant	Kg of plastic waste/ Printer
Capacity of extruder	Exogenous	Constant	Kg of plastic waste / Months / machine

Table V.1 Model equations (Continuation)

Variable	Type	Equation	Unit
Capacity of granulator	Exogenous	Constant	Kg of plastic waste / Months / machine
Capacity of means of transport for collection	Exogenous	Constant	Kg of plastic waste
Capacity per facility	Endogenous	MIN(Capacity of extruder*Number of extruders per facility; Capacity of granulator*Number of granulators per facility)	Kg of plastic waste / month / facility
CO2 avoided per Kg of recycled plastic filament	Exogenous	(CO2 emitted by manufacturing virgin plastic-CO2 emitted by plastic recycling)+(CO2 emitted by delivery virgin filament)	Kg of CO2 eq./ kg of filament
CO2 emitted by delivery virgin filament	Exogenous	Constant	Kg of CO2 eq. / kg of filament
CO2 emitted by manufacturing virgin plastic	Exogenous	Constant	Kg of CO2eq. / Kg of filament
CO2 emitted by plastic recycling	Exogenous	Constant	Kg of CO2eq. / kg of filament
CO2 emitted by plastic waste collection	Endogenous	((Distance per collection route*CO2 per kilometer)/Quantity to be collected per route)*Amount of 3D plastic waste collected/DT	Kg of CO2 eq. / Months
CO2 per kilometer	Exogenous	Constant	Kg of CO2eq. / km
Collection cost per kilogram plastic filament	Exogenous	Collection cost per route/Potential amount of recycled filament per route	Euros / Kg of filament
Collection cost per route	Exogenous	((Distance per collection route*Cost of vehicle use) + (Hours per route*Labor cost of transport))	Euros
Conversion rate	Exogenous	Constant	Kg of filament / Kg of plastic waste
Cost of vehicle	Exogenous	Constant	Euros / facility
Cost of vehicle use	Exogenous	Constant	Euros/km
Demand factor	Exogenous	Function	Institution/Months
Demand for recycled filament	Exogenous	IF (DR<=0) THEN (0) ELSE (IF (Filament consumption per printer*Number of 3D printers>DR) THEN (DR) ELSE (Filament consumption per printer*Number of 3D printers))	Kg of filament / Months
Demand for recycled filament not supplied	Endogenous	IF (Demand for recycled filament>=((Stock of recycled filament/DT)+Fabrication of recycled filament)) THEN (Demand for recycled filament-((Stock of recycled filament/DT)+Fabrication of recycled filament)) ELSE (0)	Kg of filament / Months
Demand for virgin filament	Exogenous	IF (DV<=0) THEN (0) ELSE (IF (Filament consumption per printer*Number of 3D printers > DV) THEN (DV) ELSE (Filament consumption per printer*Number of 3D printers))	Kg of filament / Months
Distance per collection route	Exogenous	Constant	km
DR (Auxiliar variable)	Endogenous	(Number of 3D printers*Filament consumption per printer)*((Sensitivity factor for price recycled vs virgin*(Price of recycled filament-Price of virgin filament)))+(Sensitivity factor for the use of recycled vs virgin filament*Performance of recycled vs virgin filament))	Kg of filament / Months
DV (Auxiliar variable)	Endogenous	(Number of 3D printers*Filament consumption per printer)*(1-((Sensitivity factor for price recycled vs virgin*(Price of recycled filament-Price of virgin filament)))+(Sensitivity factor for the use of recycled vs virgin filament*Performance of recycled vs virgin filament)))	Kg of filament / Months
Extruder price	Exogenous	Constant	Euros / facility
Fabrication capacity of the network	Endogenous	MIN(Conversion rate*Recycling capacity of the distributed network; (Storage capacity of the network/DT)*plastic to plastic waste*Conversion rate)	Kg of filament/month
Facility	Exogenous	Constant. Auxiliar variable used for dimensional consistency. (Facility = 1)	Facility

Table V.1 Model equations (Continuation)

Variable	Type	Equation	Unit
Filament consumption per printer	Exogenous	Constant	Kg of filament / Printer / Months
Filament to plastic waste	Exogenous	Constant. Auxiliar variable used for dimensional consistency. (Filament to plastic waste = 1)	Kg of plastic waste / Kg of filament
Available storage for plastic collection	Endogenous	IF (((Storage capacity of the network)*plastic to plastic waste)-(Stock of plastic waste available for recycling)-((Stock of recycled filament)*filament to plastic waste)>0) THEN (((Storage capacity of the network)*plastic to plastic waste)-(Stock of plastic waste available for recycling)-((Stock of recycled filament)*filament to plastic waste)) ELSE (0)	Kg of plastic waste
Granulator price	Exogenous	Constant	Euros/facility
Hours by collection	Endogenous	((Amount of 3D plastic waste collected/DT)/Quantity to be collected per route)*Hours per route	Hours/ Month
Hours per Kg of filament	Exogenous	Constant	Hours / Kg of filament
Hours per route	Exogenous	Distance per collection route/Average speed	Hours
Initial investment for non profit oriented recycling facilities	Exogenous	((Extruder price*Number of extruders per facility)+Cost of vehicle+(Granulator price*Number of granulators per facility)*(1-Investment subsidy))	Euros / facility
Inventory cost	Exogenous	Constant	Euros / Kg of filament
Investment subsidy	Exogenous	Constant	Dimensionless
Jobs per Hour	Exogenous	Constant	Jobs/Hour
Labor cost of processing	Exogenous	Constant	Euros/Hours
Labor cost of transport	Exogenous	Constant	Euros / Hour
Maximum potential fabrication capacity per facility	Exogenous	MIN(Capacity per facility*Conversion rate; (Storage capacity per facility/DT)*plastic to plastic waste*Recyclability rate of reference*Conversion rate)	Kg of filament/ facility / Months
Minimum amount of filament needed for implementation	Exogenous	Initial investment for non profit oriented recycling facilities/(Period of evaluation*Unit profit of recycled 3D plastic filament)	Kg of filament / facility / Month
Number of extruders per facility	Exogenous	Constant	machine/facility
Number of granulators per facility	Exogenous	Constant	machine / facility
Performance of recycled vs virgin filament	Exogenous	Constant	Dimensionless
Period of evaluation	Exogenous	Constant	Months
Plastic to plastic waste	Exogenous	Constant. Auxiliar variable used for dimensional consistency. (Plastic to plastic waste = 1)	kg of plastic waste/ Kg of plastic
Potential amount of filament from plastic waste not collected	Endogenous	IF Amount of plastic waste that cannot be collected>0 THEN (Amount of plastic waste that cannot be collected*Conversion rate*Recyclability rate of reference) /DT ELSE (0)	Kg of filament / Months
Potential amount of recycled filament per route	Exogenous	Quantity to be collected per route*Conversion rate*Recyclability rate of reference	Kg of filament
Price of recycled filament	Exogenous	Constant	Euros / Kg of filament
Price of virgin filament	Exogenous	Constant	Euros / Kg of filament
Printers per school	Exogenous	Constant	Printer/Institution
Quantity to be collected per route	Exogenous	MIN(MIN((Number of 3D printers*Box capacity); Capacity of means of transport for collection); Storage capacity per facility*Facility*plastic to plastic waste)	Kg of plastic waste
Recyclability rate of recycled 3D plastic waste	Exogenous	Constant	Dimensionless
Recyclability rate of reference	Exogenous	MIN(Recyclability rate of recycled 3D plastic waste; Recyclability rate of virgin 3D plastic waste)	Dimensionless

Table V.1 Model equations (Continuation)

Variable	Type	Equation	Unit
Recyclability rate of reference	Exogenous	MIN(Recyclability rate of recycled 3D plastic waste; Recyclability rate of virgin 3D plastic waste)	Dimensionless
Recyclability rate of virgin 3D plastic waste	Exogenous	Constant	Dimensionless
Recycling capacity of the distributed network	Endogenous	Number of non profit oriented recycling facilities*Capacity per facility	Kg of plastic waste / Months
Recycling cost	Exogenous	Constant	Euros / Kg of filament
Scrap rate of recycled 3D plastic	Exogenous	Constant	Kg of plastic waste / Kg of filament
Scrap rate of virgin 3D plastic	Exogenous	Constant	Kg of plastic waste / Kg of filament
Sensitivity factor for price recycled vs virgin	Exogenous	Constant	Kg of filament / Euros
Sensitivity factor for the use of recycled vs virgin filament	Exogenous	Constant	Dimensionless
Social cost per Kg of CO2	Exogenous	Constant	Euros/ Kg of CO2 eq.
Storage capacity of the network	Endogenous	Storage capacity per facility*Number of non profit oriented recycling facilities	Kg of plastic
Storage capacity per facility	Exogenous	Constant	Kg of plastic/ facility
Total amount of plastic waste available for recycling	Endogenous	(Stock of plastic waste available for recycling/DT)+(Amount of recycled 3D plastic waste available for recycling + Amount of virgin 3D plastic waste available for recycling)	Kg of plastic waste / Months
Unit cost of recycled 3D plastic filament	Exogenous	Inventory cost+(Labor cost of processing*Hours per Kg of filament)+Recycling cost + Collection cost per kilogram plastic filament	Euros / Kg of filament
Unit profit of recycled 3D plastic filament	Exogenous	Price of recycled filament-Unit cost of recycled 3D plastic filament	Euros / Kg of filament
Virgin filament sales	Endogenous	Demand for virgin filament + Demand for recycled filament not supplied	Kg of filament / Months

5.6. Application of the proposed system dynamic model

Similar to the previous chapter the model has been applied to the case of the Lorraine Fab Living Lab (LFL2) for the recycling of 3D printing PLA plastic waste from schools and high schools in Nancy, France (see [chapter IV section 4.4](#) for more details). Considering the above, the following baseline scenario is studied:

- **Baseline scenario:** LF2L has already invested in the machinery to carry out the process of collecting and recycling of plastics (extruder machine, granulator and means of transport). As sources of waste, only PLA plastic waste from 3D printing is considered. This plastic waste will be collected from the same schools and high schools that will be supplied.

Table V.2. Assumptions established for the model construction

Assumption	Description
Assumption 1	Because the users of 3D printing considered in this system correspond to educational institutions, the demand for recycled filament is assumed as inelastic, i.e. the amount of filament demanded and consumed does not depend on the price of the filaments.
Assumption 2	The demand for recycled and virgin filament has been represented by a function, which determines the fraction, of the total demand for filament, which demands recycled and virgin filament. The fraction of total demand that prefers recycled and virgin filament is determined by a linear equation. This linear equation considers the performance of recycled versus virgin filament and the difference between the prices of these filaments. See Appendix V.1 for a more detailed explanation.
Assumption 3	It is assumed that the amount of virgin filament demanded is totally sold.
Assumption 4	It is assumed that the sales of recycled filament correspond to the demand for this filament (if there is stock).
Assumption 5	The implementation of new non-profit recycling facilities is based on three criteria: Recycling capacity, return on investment, and availability of plastic waste. New non-profit oriented facilities will be implemented if (1) the demand for recycled filament exceeds the capacity of recycling, (2) the demand to be covered by the new facility allows recovering the investment in 5 years, and (3) there are plastic wastes available to fabricate the necessary amount of filament.
Assumption 6	Due to the condition of recovery of the investment in 5 years (Assumption 5). If a recycling facility is installed, it lasts 5 years. A reinvestment is required to maintain the recycling facility in operation.
Assumption 7	In order to make the collection process more economically and environmentally efficient, a condition has been imposed. First, collection path obtained from the application of the optimization model in Chapter IV has been considered. From that application, the distance and time of the route have been obtained. Then, it has been imposed in the model that this route will be carried out only if the amount to be collected is greater than a previously defined amount (see Appendix V.2 for a more detailed explanation). In this case, it has been assumed that the collection process will take place once a container placed at the side of each printer is completely filled with plastic waste. Since the filament consumption per printer is considered as constant and the scrap rate is also considered as constant (same value for both materials), these containers will be filled at the same time. Therefore, the collection criteria (predefined amount to carry out the collection route) has been set as the multiplication of the box capacity by the number of printers in the territory.

[Table V.3](#) presents the values of the exogenous variables and the initial values for the stock variables defined for the baseline scenario. Among these parameters, the demand factor is modeled as a step function. The demand is modelled in this way because, as presented in [Table V.4](#), it is known that two of the 23 schools/high schools have a 3D printer. This information has been obtained by

applying a survey³⁵ to the teachers of the schools and high schools of the Lorraine region during November 2018. To model the demand, it is assumed that every 6 months, five schools will buy two 3D printer. Therefore, it is expected that in less than 3 years (specifically in 25 months) all the schools and high schools considered would have 3D printers.

Table V.3. Parameter value for base scenario

Variable	Scenario	Unit	Reference
Amount of recycled 3D plastic waste available for collection(t)	INIT Amount of recycled 3D plastic waste available for collection = 0	Kg of plastic waste	Initial scenario
Amount of virgin 3D plastic waste available for collection(t)	INIT Amount of virgin 3D plastic waste available for collection = 0	Kg of plastic waste	Initial scenario
Global profit(t)	INIT Global profit = -Initial investment for non profit oriented recycling facilities*Number of non profit oriented recycling facilities	Euros	Initial scenario
Number of 3D printers(t)	INIT Number of 3D printers = 0	Printer	Initial scenario
Number of non profit oriented recycling facilities(t)	INIT Number of non profit oriented recycling facilities=1	facility	Initial scenario
Stock of plastic waste available for recycling(t)	INIT Stock of plastic waste available for recycling = 0	Kg of plastic waste	Initial scenario
Stock of recycled 3D plastic waste collected(t)	INIT Stock of recycled 3D plastic waste collected= 0	Kg of plastic waste	Initial scenario
Stock of recycled filament(t)	INIT Stock of recycled filament = 0	Kg of filament	Initial scenario
Stock of virgin 3D plastic waste collected(t)	INIT Stock of virgin 3D plastic waste collected = 0	Kg of plastic waste	Initial scenario
Total amount of plastic waste recycled(t)	INIT Total amount of plastic waste recycled=0	Kg of plastic waste	Initial scenario
Total amount of recycled filament supplied(t)	INIT Total amount of recycled filament supplied=0	Kg of filament	Initial scenario
Total CO2 saved(t)	INIT Total CO2 saved=0	Kg of CO2 eq.	Initial scenario
Total job creation(t)	INIT Total job creation= 0	Jobs	Initial scenario
Total social cost avoided(t)	INIT Total social cost avoided= 0	Euros	Initial scenario
Box capacity	0.2	Kg of plastic waste/ Printer	Assumption of LF2L
Capacity of extruder	35	Kg of plastic waste / Months / machine	Estimated based on [39]
Capacity of granulator	280	Kg of plastic waste / Months / machine	Estimated based on [247]
Capacity of means of transport for collection	415	Kg of plastic waste	Suzuki Motor Corporation ³⁶
CO2 emitted by delivery virgin filament	4.229	Kg of CO2 eq. / kg of filament	Estimated based on [246]
CO2 emitted by manufacturing virgin plastic	1.8	Kg of CO2 eq. / Kg of filament	[245]
CO2 emitted by plastic recycling	0.52	Kg of CO2 eq. / kg of filament	[14]
CO2 per kilometer	0.099	Kg of CO2 eq. / km	Suzuki Motor Corporation ³⁷
Conversion rate	0.9	Kg of filament / Kg of plastic waste	LF2L
Cost of vehicle	0	Euros / facility	Not considered due to the possibility of renting a vehicle

³⁵https://docs.google.com/forms/d/e/1FAIpQLSf_EWlqMFUA22UZjX-gMTTg0l9mcZVr-sDO5JhjfVzjZLFqcA/viewform?usp=sf_link

³⁶ Suzuki Motor Corporation, "Small Car Loaded with Big Ideas," 2014. [Online]. Available: <https://www.globalsuzuki.com/automobile/lineup/celerio/index.html>. [Accessed: 20-Dec-2018].

³⁷ Suzuki Motor Corporation, "Small Car Loaded with Big Ideas," 2014. [Online]. Available: <https://www.globalsuzuki.com/automobile/lineup/celerio/index.html>. [Accessed: 20-Dec-2018].

Table V.3. Parameter value for base scenario (continuation)

Variable	Scenario	Unit	Reference
Cost of vehicle use	0.15	Euros/km	LF2L
Demand factor	GRAPH(TIME) Points: (0,00, 0,0), (1,00, 0,0), (2,00, 0,0), (3,00, 0,0), (4,00, 0,0), (5,00, 0,0), (6,00, 5,0), (7,00, 0,0), (8,00, 0,0), (9,00, 0,0), (10,00, 0,0), (11,00, 0,0), (12,00, 5,0), (13,00, 0,0), (14,00, 0,0), (15,00, 0,0), (16,00, 0,0), (17,00, 0,0), (18,00, 5,0), (19,00, 0,0), (20,00, 0,0), (21,00, 0,0), (22,00, 0,0), (23,00, 0,0), (24,00, 6,0), (25,00, 0,0), (26,00, 0,0), (27,00, 0,0), (28,00, 0,0), (29,00, 0,0), (30,00, 0,0), (31,00, 0,0), (32,00, 0,0), (33,00, 0,0), (34,00, 0,0), (35,00, 0,0), (36,00, 0,0), (37,00, 0,0), (38,00, 0,0), (39,00, 0,0), (40,00, 0,0), (41,00, 0,0), (42,00, 0,0), (43,00, 0,0), (44,00, 0,0), (45,00, 0,0), (46,00, 0,0), (47,00, 0,0), (48,00, 0,0), (49,00, 0,0), (50,00, 0,0), (51,00, 0,0), (52,00, 0,0), (53,00, 0,0), (54,00, 0,0), (55,00, 0,0), (56,00, 0,0), (57,00, 0,0), (58,00, 0,0), (59,00, 0,0), (60,00, 0,0)	Institution/Months	Assumption
Demand for recycled filament	Demand for recycled filament = IF (DR<=0) THEN (0) ELSE (IF (Filament consumption per printer*Number of 3D printers>DR>0) THEN (DR) ELSE (Filament consumption per printer*Number of 3D printers))	Kg of filament / Months	Assumption
Demand for virgin filament	Demand for virgin filament = IF (DV<=0) THEN (0) ELSE (IF (Filament consumption per printer*Number of 3D printers>DV>0) THEN (DV) ELSE (Filament consumption per printer*Number of 3D printers))	Kg of filament / Months	Assumption
DR	DR = (Number of 3D printers*Filament consumption per printer) *((Sensitivity factor for price recycled vs virgin*(Price of recycled filament-Price of virgin filament)) + (Sensitivity factor for the use of recycled vs virgin filament*Performance of recycled vs virgin filament))	Kg of filament / Months	Assumption
DV	DV = (Number of 3D printers*Filament consumption per printer) *(1- ((Sensitivity factor for price recycled vs virgin*(Price of recycled filament-Price of virgin filament)) + (Sensitivity factor for the use of recycled vs virgin filament*Performance of recycled vs virgin filament)))	Kg of filament / Months	Assumption
Distance per collection route	26.515	km	Estimated based on optimization model of chapter IV
Extruder price	859	Euros / facility	Estimated based on [39]
Filament consumption per printer	0.91	Kg of filament / Printer/ Months	Average consumption of schools and high schools in the region that have 3D printers (survey analysis)

Table V.3. Parameter value for base scenario (continuation)

Variable	Scenario	Unit	Reference
Granulator price	1718	Euros/facility	Estimated based on [247]
Hours per Kg of filament	0.05	Hours / Kg of filament	LF2L
Average speed	21	Km / Hour	Average speed considered in optimization model of chapter IV
Inventory cost	0.50	Euros / Kg of filament	LF2L
Investment subsidy	0	Dimensionless	Initial Scenario
Jobs per Hour	1/140	Jobs/Hour	LF2L (Considering a workload of 35 hours per week)
Labor cost of processing	17	Euros/Hours	LF2L
Labor cost of transport	17	Euros / Hour	LF2L
Number of extruders per facility	1	machine/facility	LF2L
Number of granulators per facility	1	machine / facility	LF2L
Performance of recycled vs virgin filament	1 (equal performance)	Dimensionless	LF2L
Period of evaluation	60	Months	LF2L
Price of recycled filament	20.62	Euros / Kg of filament	Atome3D ³⁸
Price of virgin filament	19.99	Euros / Kg of filament	Atome3D ³⁹
Printers per school	2	Printer/Institution	Average number of 3D printers in schools in the region (survey analysis)
Recyclability rate of recycled 3D plastic waste	0.5	Dimensionless	LF2L
Recyclability rate of virgin 3D plastic waste	0.8	Dimensionless	LF2L
Recycling cost	0.92	Euros / Kg of filament	[27]
Scrap rate of recycled 3D plastic	0.2	Kg of plastic waste / Kg of filament	Average scrap rate of schools in the region (survey analysis)
Scrap rate of virgin 3D plastic	0.2	Kg of plastic waste / Kg of filament	Average scrap rate of schools in the region (survey analysis)
Sensitivity factor for price recycled vs virgin	-0.05	Kg of filament / Euros	Assumption
Sensitivity factor for the use of recycled vs virgin filament	0.5	Dimensionless	Assumption
Social cost per Kg of CO2	46.5/1000	Euros/ Kg of CO2 eq.	Estimated based on ⁴⁰
Storage capacity per facility	20	Kg of plastic/ facility	LF2L

³⁸ "Atome3D." [Online]. Available: <https://www.atome3d.com/collections/filaments-recycles/products/formfutura-reform-rpla-blanc-white-1-75-mm-1-kg?variant=13384998977595%0A>.

³⁹ "Atome3D." [Online]. Available: <https://www.atome3d.com/collections/filaments-pla/products/raise3d-pla-colorful-blanc-white-1-75mm-1kg?variant=32670721048714%0A>.

⁴⁰ K. Rennert and C. Kingdon, "Social Cost of Carbon 101. A review of the social cost of carbon, from a basic definition to the history of its use in policy analysis.," 2019

Table V.4. Current number of 3D printers' schools and high schools

School / High School	Number of 3D printers
Lycée professionnel Paul Louis Cyffle	0
Collège/Lycée Charles De Foucauld	0
Lycée professionnel Claude Daunot	0
Collège/Lycée Saint Dominique	0
Lycée général et technologique Jeanne D'Arc	0
Collège/Lycée Notre Dame Saint Sigisbert	1
Collège Alfred Mezieres	0
Lycée professionnel Les Métiers De La Beauté	0
Collège La Craffe	0
Lycée général et technologique Henri Poincare	0
Collège Guynemer	0
Lycée général et technologique Henri Loritz	6
Collège/Lycée Saint Leon Ix	0
Collège Louis Armand	0
Lycée professionnel Marie Immaculee	0
Collège Du Sacre Coeur	0
Collège/Lycée Frederic Chopin	0
Lycée technique Compagnie De Formation-Pigier	0
Collège/Lycée général et technologique Georges De La Tour	0
Lycée professionnel Pierre De Coubertin	0
Collège Collège Montessori Grand-Est	0
Lycée professionnel Jean Prouve	0
Collège Jean Lamour	0

5.7. Model validation

The literature suggests 12 tests for the validation of system dynamics models [13]. For the validation of this model, it has been possible to carry out 7 of the 12 tests proposed. Table V.5 summarizes the validation tests carried out and explains the ones that could not be carried out.

Table V.5. Validation tests conducted

Test	Purpose of test	Tools and procedure used
Boundary Adequacy	Evaluate if the boundaries of the model are adequate for its purpose.	During the development of the model, successive meetings have been conducted with LF2L experts, in which the elements considered in the model have been presented using the diagrams shown in this document.
Structure assessment	Evaluate if the model structure is consistent with the knowledge of the real system	During the development of the model, successive meetings have been conducted with LF2L experts, in which the structure of the model has been presented using the diagrams shown in this document. The equations have been reviewed and conform to the physical laws of conservation
Dimensional consistency	Analyze whether the elements of the equations and the results of the operations are dimensionally consistent	Dimensional consistency has been tested by reviewing equations and using Stella software.

Table V.5. Validation tests conducted (Continuation)

Test	Purpose of test	Tools and procedure used
Parameter assessment	Evaluate if the values and the calculation of the parameters are consistent with the knowledge of the system.	Some parameter values have references in the literature. The parameters without reference (Demand for virgin or recycled filament, recyclability rate, etc) has been validated with LF2L experts.
Extreme condition test	Evaluate whether the model is robust in extreme conditions (extreme value of parameters).	The equations have been evaluated under extreme conditions (virgin filament price, recycled filament price, scrap rates, storage capacity, Investment and Capacity of extruder and granulator) resulting in a real behavior. As a result of this analysis, a utility condition has been imposed for waste collection and filament fabrication. Specifically, these activities will be carried out only if the utility of the recycled filament is positive. The equations have been reviewed and conform to the basic physical laws.
Integration test	Examine whether the results of the SD model are sensitive to the choice of the numerical integration method and/or the time step.	The time step has been decreased to 1/8 dt (dt = 1 month) and the results of the model were not sensitive.
Behavior Reproduction Test	Assess whether the model is capable of reproducing the behavior of the system under study	This test could not be carried out, because the system under study (distributed recycling of plastic for 3D printing) is a proposal and is not yet implemented. Therefore, it has not been possible to obtain feedback by observing the system.
Behavior Anomaly Tests	Examine the importance of relationships or formulations that are not possible to establish by statistical means.	This test has not been carried out as it was not needed.
Family Member Tests	Assess whether the model is capable of imitating the behavior of the system in other scenarios/contexts.	This test could not be carried out, because the system under study (distributed recycling of plastic for 3D printing) is a proposal and is not yet implemented. Therefore, it has not been possible to obtain feedback by observing the system.
Surprise Behavior Tests	Observe if behaviors thrown by the model, which had not been previously considered, occur truly in the system.	This test could not be carried out, because the system under study (distributed recycling of plastic for 3D printing) is a proposal and is not yet implemented. Therefore, it has not been possible to obtain feedback by observing the system.
Sensitivity Analysis	Evaluate whether the conclusions change in ways important to the purpose when assumptions are varied over the plausible range of uncertainty.	Sensitivity analysis has been carried out to a certain set of variables. For more details see the section of sensitivity analysis.
System Improvement Tests	Assess whether the system has effectively helped to solve the problem for which the system has been modeled	This test could not be carried out, because the system under study (distributed recycling of plastic for 3D printing) is a proposal and is not yet implemented.

5.8. Results

In this section, the results obtained for the base scenario are presented. The study period has been 10 years with a monthly time step. [Table V.6](#) presents the values obtained for each indicator. [Figures V.15-20](#) show the graphs obtained for each indicator. It should be mentioned that, as an additional indicator in this analysis, the number of recycling facilities has been considered, because the number of recycling facilities to be implemented (non-profit oriented recycling facilities if we consider this case study) is an important parameter in the context of distributed plastic recycling. Under this context, if more small-scale recycling facilities are implemented, more plastic waste could potentially be recycled. However, a higher availability of plastic waste does not mean that a recycling facility will be implemented. Implementation also depends on other aspects such as profitability which is why the consideration of non-profit oriented facilities is a priori interesting to consider.

Table V.6. Results

Year	Global profit (euros)	Total amount of plastic waste recycled (Kg of plastic waste)	CO ₂ not emitted (saved) (Kg of CO ₂ eq.)	Social cost avoided (euros)	Total Job creation (Jobs)	Number of recycling facilities
Year 1	-2569.45	12.29	47.83	2.22	0.14	1
Year 2	-2226.55	56.58	241.15	11.21	0.24	1
Year 3	-1406.30	129.72	577.54	26.86	0.36	1
Year 4	-587.04	202.77	913.49	42.48	0.47	1
Year 5	232.21	275.82	1249.44	58.10	0.58	1
Year 6	-1443.60	356.18	1618.99	75.28	0.71	1
Year 7	-624.35	429.24	1954.94	90.90	0.82	1
Year 8	194.91	502.29	2290.89	106.53	0.94	1
Year 9	1096.09	582.65	2660.44	123.71	1.06	1
Year 10	1915.34	655.70	2996.39	139.33	1.18	1

As can be observed in [Table V.6](#) and [Figures V.15-20](#), the results show, from the economic point of view, that the investment (2577 euros considering extrusion and granulator machine) is recovered in less than 5 years. After 5 years, a reinvestment could be made, since the conditions imposed for the implementation of a new facility (investment recovery condition, capacity condition and waste availability condition) are met. Considering the environmental indicators, the results show that a total of 655.70 kg of plastic waste would be recycled by the system in 10 years and that a total of 2996.39 kg of CO₂ eq (equivalent to the carbon footprint of 0.27 inhabitants in France in 2018 ⁴¹) would be avoided due to the recycling process. From the social point of view, a social cost equivalent to 58.10 euros would be avoided in 5 years and 139.33 euros in 10 years. In relation to job creation, the equivalent of 1.18 months of work would be created in 10 years. Finally, only one recycling facility would be needed to carry out the entire process.

⁴¹ Commissariat général au développement durable, "L'empreinte carbone des Français," 2020.



Figure V.15. Global profit of baseline scenario



Figure V.16. Total amount of plastic waste recycled in baseline scenario

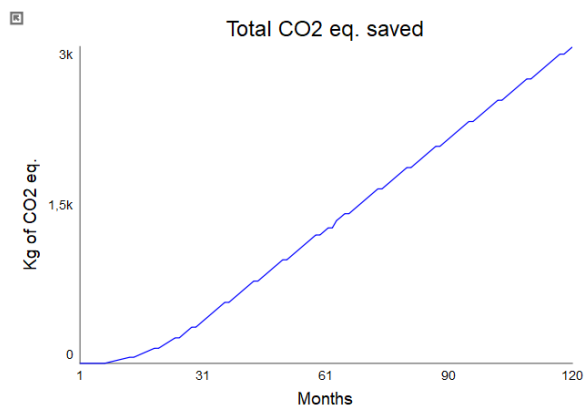


Figure V.17. Total amount of CO₂ eq. saved in baseline scenario

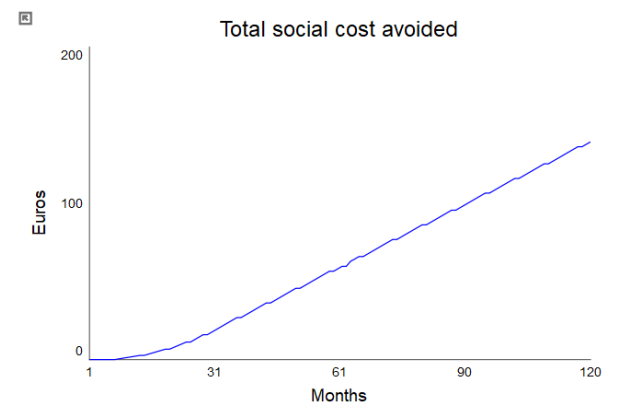


Figure V.18. Total social cost avoided in baseline scenario

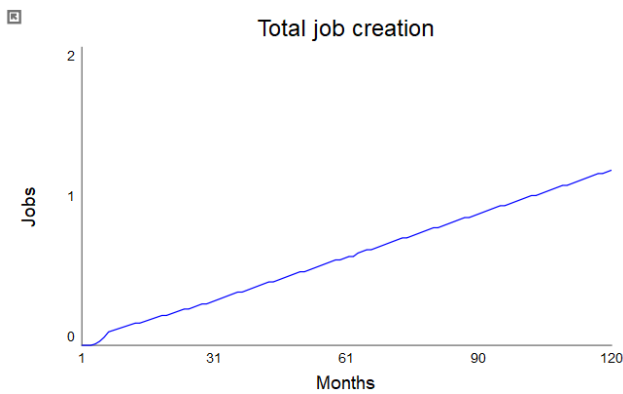


Figure V.19. Total job creation in baseline scenario

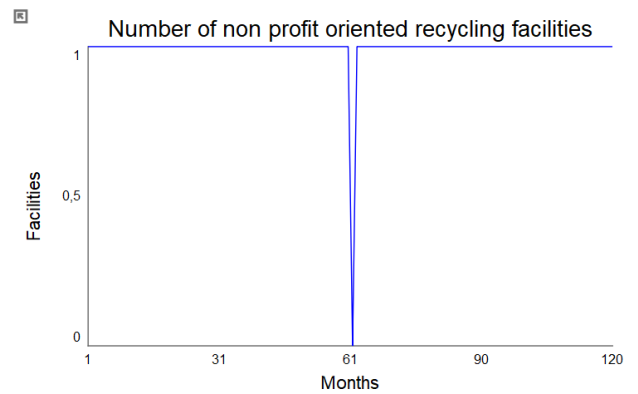


Figure V.20. Number of non-profit oriented facilities in baseline scenario

5.9. Sensitivity Analysis

In order to define the way in which the most important context variables of the system impact on it, a sensitivity analysis has been carried out. Knowing the sensitivity of these variables allows decision-makers to identify those variables that favor or disfavor the development of this recycling approach. For the sensitivity analysis, seven variables have been varied separately: Price of recycled filament, Price of virgin filament, Filament consumption per printer, Investment subsidy, Printers per school, Scrap rate and Labor cost. [Table V.7](#) details the value ranges for each parameter. Then, the sensitivity

on the indicators due to the variation of these parameters has been analyzed separately. The results of the sensitivity analysis are presented below.

Table V.7. Input and output indicators in sensitivity analysis

Input Indicators	Units	Range	Outputs Indicators
Price of recycled filament	Euros/Kg of filament	[5 - 35]	1. Global profit 2. Amount of plastic waste recycled 3. CO ₂ eq. Savings 4. Social cost avoided 5. Job creation 6. Number of recycling facilities
Price of virgin filament	Euros/Kg of filament	[5 - 35]	
Filament consumption	(Kg of filament / printer/month)	[0.8 - 4]	
Investment subsidy	Dimensionless	[0 - 1]	
Printers per school	3D printers / institution	[2 - 6]	
Scrap rate	Dimensionless	[0.2 - 1]	
Labor cost per hour	Euros/hour	[17 - 25]	

5.9.1. Price of recycled filament

This section presents the results obtained from the sensitivity analysis of the recycled filament price. [Figures V.21-26](#) present the cumulative results over the analysis period for each indicator.

The results obtained show a high sensitivity of the indicators (except for job creation) to the variations in the price of recycled filament. Specifically, if the price of the recycled filament is between 20 euros and 32 euros, it is possible to recover the investment in 5 years and obtain a positive profit in 10 years. On the other hand, a price higher than 29 euros causes a very low demand, which does not allow recovering the investment. Considering the other indicators, these are very sensitive. It is mainly due to the variation in the demand for recycled filament, which affects the quantities recycled and therefore, these indicators.

5.9.2. Price of virgin filament

This section presents the results obtained from the sensitivity analysis of the virgin filament price. [Figures V.27-32](#) present the results obtained for each indicator.

The results of the variation of the price of virgin filament show a medium sensitivity of the indicators for a price of virgin filament greater than 14 euros. This is because for a virgin filament price greater than 14 euros, the demand for recycled filament is greater than the amount of filament that the system is capable of fabricating. This is because the conditions are not met for the implementation of another facility, therefore the amount of recycled filament provided in each period does not vary in each scenario. As a consequence of the same, the other indicators hardly vary. In the case where the price of virgin filament is less than 14 euros, the demand and utility of the recycled filament is too low to recover the investment.

5.9.3. Filament consumption

This section presents the results obtained from the sensitivity analysis of the filament consumption per printer. [Figures V.33-38](#) present the results obtained for each indicator.

The results show a high sensitivity of the indicators to the variation of the filament consumption per printer. A higher consumption causes a higher demand and a higher waste generation. Therefore, this causes that more recycled plastic filament can be fabricated, which increases the global profit and the value of the other indicators. In addition, higher filament consumption creates the conditions (capacity vs. demand, investment recovery and waste availability) for the implementation of new recycling facilities (requiring two facilities in some scenarios).

5.9.4. Investment subsidy

This section presents the results obtained from the sensitivity analysis of the Investment subsidy. [Figures V.39-44](#) present the results obtained for each indicator.

An increased investment subsidy could promote the implementation of new recycling facilities to meet the demand for recycled filament. In addition, a subsidy allows for a lower return on investment. However, the availability of plastic waste to fabricate recycled filament is an important factor in this system. Despite a large subsidy available, the demand for recycled filament and the amount of plastic waste available does not allow the implementation of a new recycling facilities. Therefore, the subsidy factor only changes the global profit.

5.9.5. Printers per school

This section presents the results obtained from the sensitivity analysis the printers considered per school. [Figures V.45-50](#) present the results obtained for each indicator.

The results obtained show a high sensitivity of the indicators to variations in the number of printers demanded per school/high school. A greater number of printers demanded, causes a greater demand for both recycled and virgin filament. An increase in both demands causes a greater amount of waste available for recycling, which results in an increase in the value of these indicators. An increase in demand and availability of waste causes that new facilities can be implemented. This finally results in more plastic waste recycled and recycled filament fabricated to cover the demand.

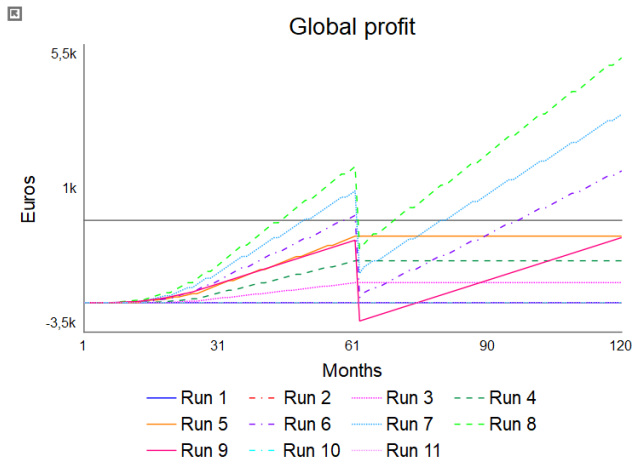


Figure V.21. Price of recycled filament and Global profit
Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

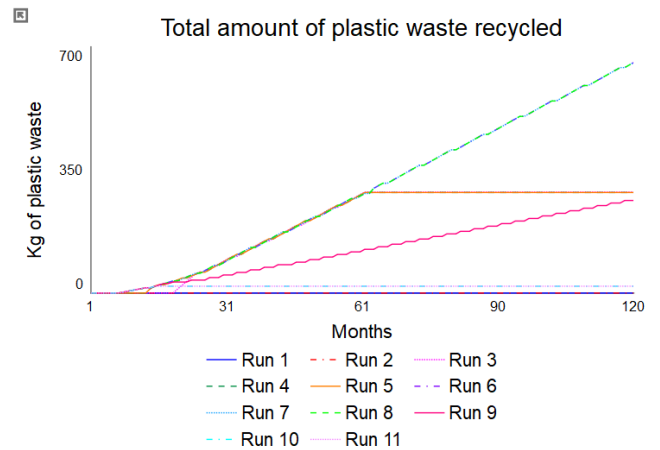


Figure V.22. Price of recycled filament and Total amount of plastic waste recycled
Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

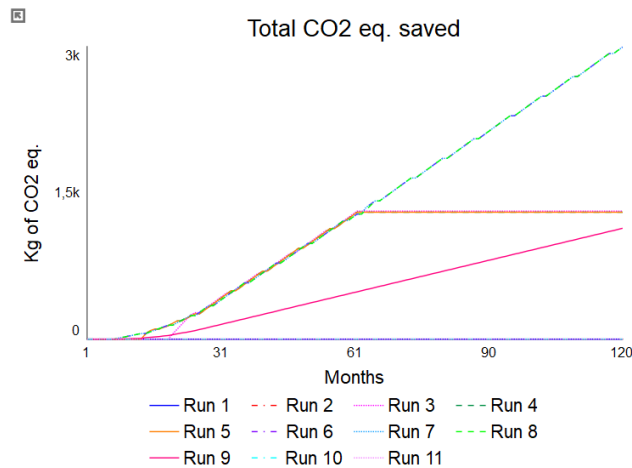


Figure V.23. Price of recycled filament and Total CO₂ eq. saved
Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

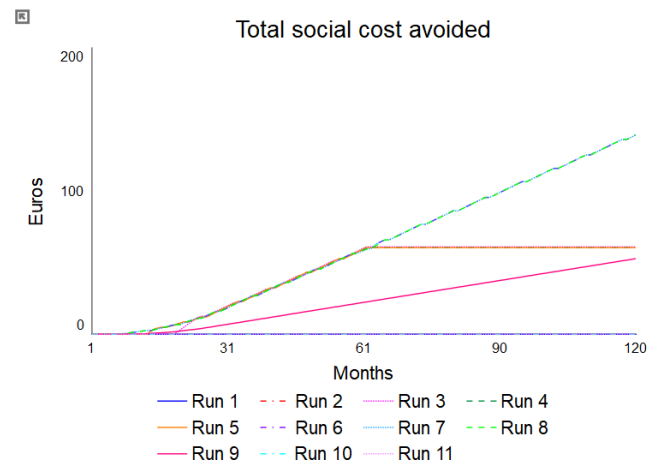


Figure V.24. Price of recycled filament and Total social cost avoided
Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

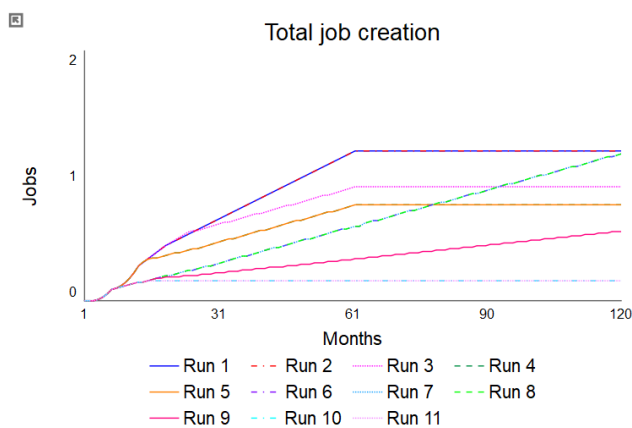


Figure V.25. Price of recycled filament and Total job creation
Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

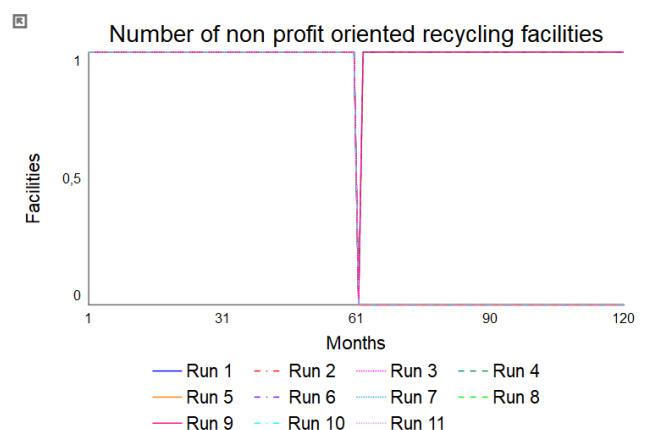


Figure V.26. Price of recycled filament and Number of non-profit oriented facilities
Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

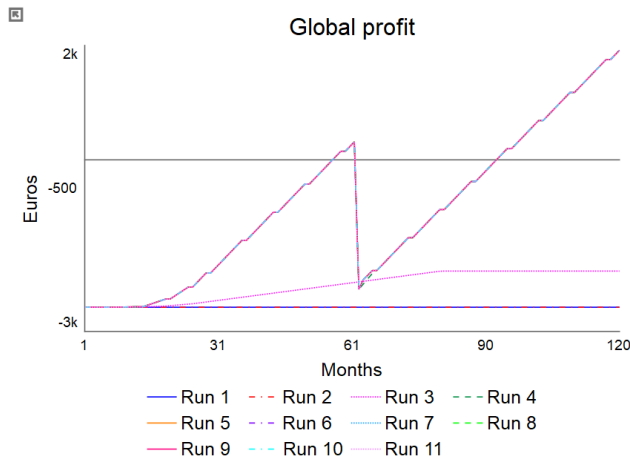


Figure V.27. Price of virgin filament and Global profit
 Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
 Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35



Figure V.28. Price of virgin filament and Total amount of plastic waste recycled
 Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
 Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

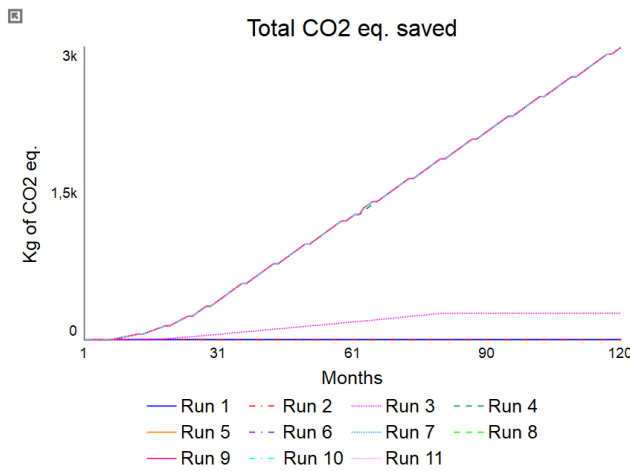


Figure V.29. Price of virgin filament and Total CO₂ eq. saved
 Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
 Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35



Figure V.30. Price of virgin filament and Total social cost avoided
 Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
 Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

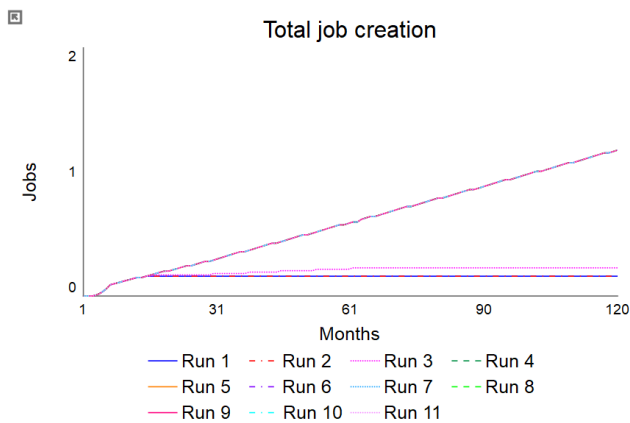


Figure V.31. Price of virgin filament and Total job creation
 Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
 Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

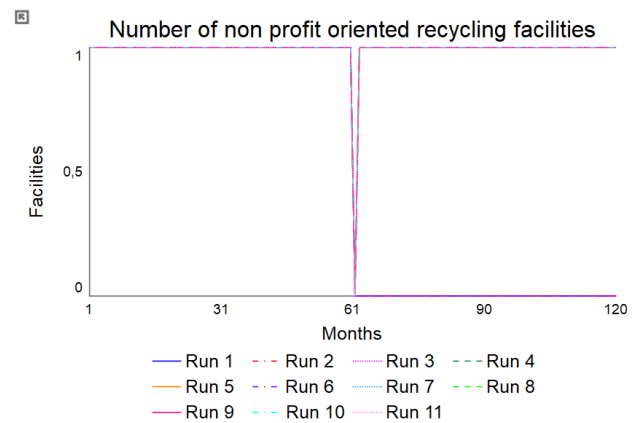


Figure V.32. Price of virgin filament and Number of non-profit oriented facilities
 Run 1: 5, Run 2: 8, Run 3: 11, Run 4: 14, Run 5: 17, Run 6: 20,
 Run 7: 23, Run 8: 26, Run 9: 29, Run 10: 32, Run 11: 35

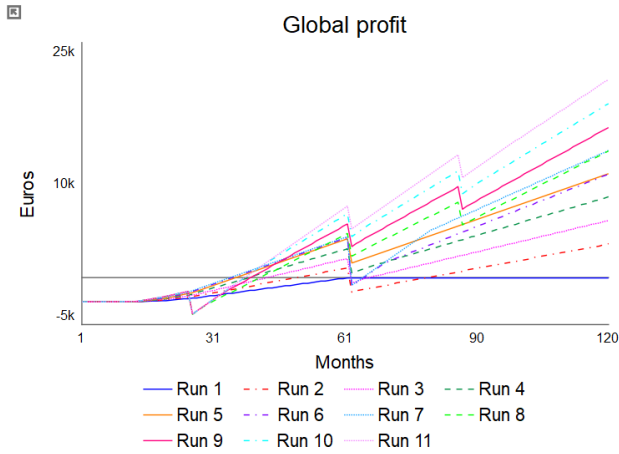


Figure V.33. Filament consumption and Global profit
 Run 1: 0.8, Run 2: 1.12, Run 3: 1.44, Run 4: 1.76, Run 5: 2.08,
 Run 6: 2.40, Run 7: 2.72, Run 8: 3.04, Run 9: 3.36, Run 10: 3.68,
 Run 11: 4.00



Figure V.34. Filament consumption and Total amount of plastic waste recycled
 Run 1: 0.8, Run 2: 1.12, Run 3: 1.44, Run 4: 1.76, Run 5: 2.08, Run 6: 2.40, Run 7: 2.72, Run 8: 3.04, Run 9: 3.36, Run 10: 3.68, Run 11: 4.00

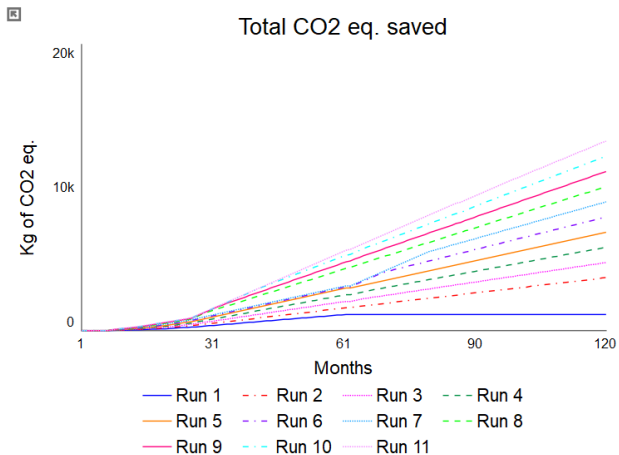


Figure V.35. Filament consumption and Total CO₂ eq. saved
 Run 1: 0.8, Run 2: 1.12, Run 3: 1.44, Run 4: 1.76, Run 5: 2.08,
 Run 6: 2.40, Run 7: 2.72, Run 8: 3.04, Run 9: 3.36, Run 10: 3.68,
 Run 11: 4.00

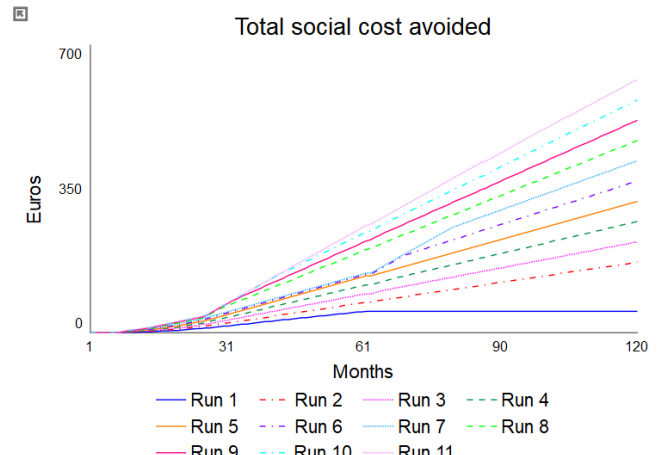


Figure V.36. Filament consumption and Total social cost avoided
 Run 1: 0.8, Run 2: 1.12, Run 3: 1.44, Run 4: 1.76, Run 5: 2.08, Run 6: 2.40, Run 7: 2.72, Run 8: 3.04, Run 9: 3.36, Run 10: 3.68, Run 11: 4.00



Figure V.37. Filament consumption and Total job creation
 Run 1: 0.8, Run 2: 1.12, Run 3: 1.44, Run 4: 1.76, Run 5: 2.08,
 Run 6: 2.40, Run 7: 2.72, Run 8: 3.04, Run 9: 3.36, Run 10: 3.68,
 Run 11: 4.00

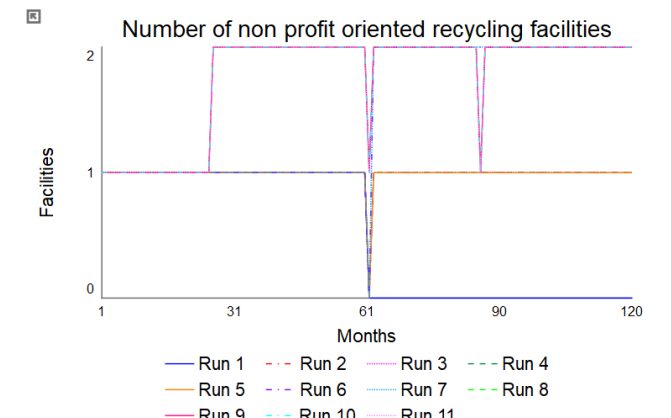


Figure V.38. Filament consumption and Number of non-profit oriented facilities
 Run 1: 0.8, Run 2: 1.12, Run 3: 1.44, Run 4: 1.76, Run 5: 2.08, Run 6: 2.40, Run 7: 2.72, Run 8: 3.04, Run 9: 3.36, Run 10: 3.68, Run 11: 4.00

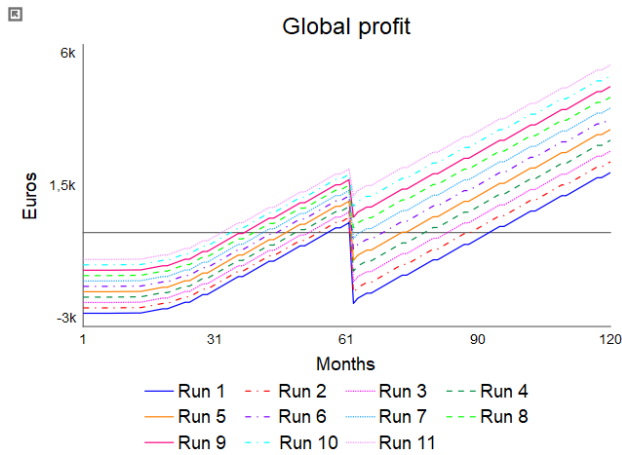


Figure V.39. Investment subsidy and Global profit
 Run 1: 0, Run 2: 0.1, Run 3: 0.2, Run 4: 0.3, Run 5: 0.4, Run 6: 0.5, Run 7: 0.6, Run 8: 0.7, Run 9: 0.8, Run 10: 0.9, Run 11: 1



Figure V.40. Investment subsidy and Total amount of plastic waste recycled
 Run 1: 0, Run 2: 0.1, Run 3: 0.2, Run 4: 0.3, Run 5: 0.4, Run 6: 0.5, Run 7: 0.6, Run 8: 0.7, Run 9: 0.8, Run 10: 0.9, Run 11: 1

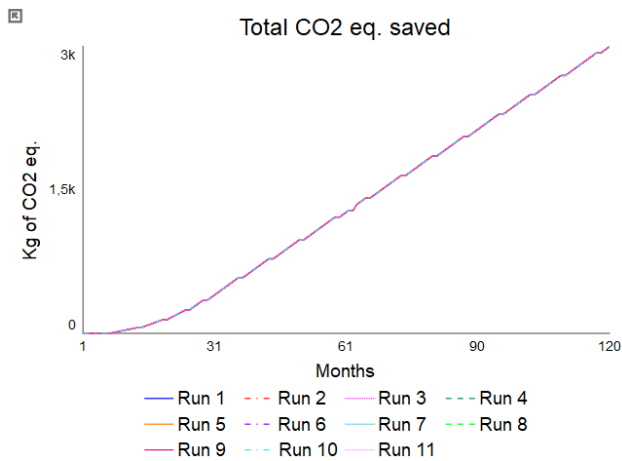


Figure V.41. Investment subsidy and Total CO₂ eq. saved
 Run 1: 0, Run 2: 0.1, Run 3: 0.2, Run 4: 0.3, Run 5: 0.4, Run 6: 0.5, Run 7: 0.6, Run 8: 0.7, Run 9: 0.8, Run 10: 0.9, Run 11: 1

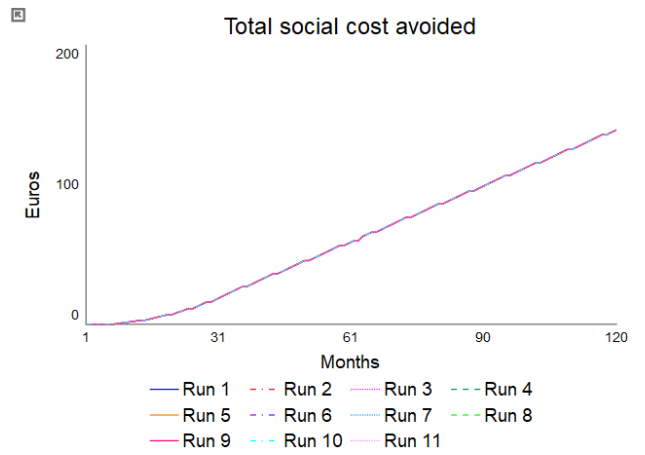


Figure V.42. Investment subsidy Total social cost avoided
 Run 1: 0, Run 2: 0.1, Run 3: 0.2, Run 4: 0.3, Run 5: 0.4, Run 6: 0.5, Run 7: 0.6, Run 8: 0.7, Run 9: 0.8, Run 10: 0.9, Run 11: 1

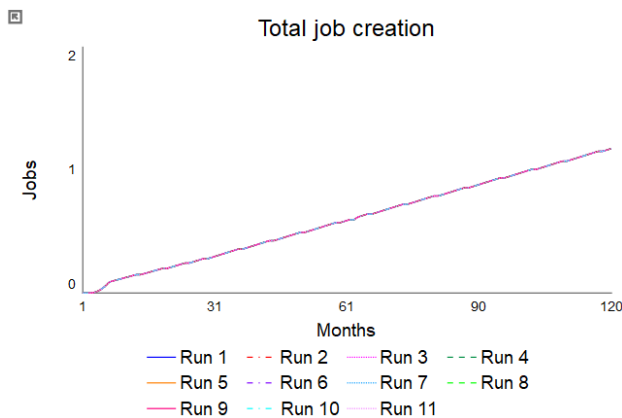


Figure V.43. Investment subsidy and Total job creation
 Run 1: 0, Run 2: 0.1, Run 3: 0.2, Run 4: 0.3, Run 5: 0.4, Run 6: 0.5, Run 7: 0.6, Run 8: 0.7, Run 9: 0.8, Run 10: 0.9, Run 11: 1

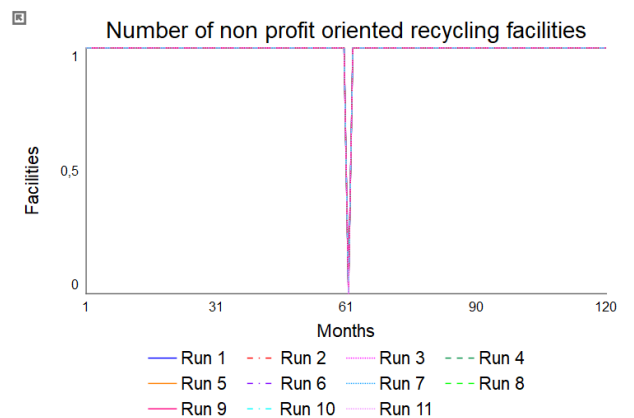


Figure V.44. Investment subsidy and Number of non-profit oriented facilities
 Run 1: 0, Run 2: 0.1, Run 3: 0.2, Run 4: 0.3, Run 5: 0.4, Run 6: 0.5, Run 7: 0.6, Run 8: 0.7, Run 9: 0.8, Run 10: 0.9, Run 11: 1

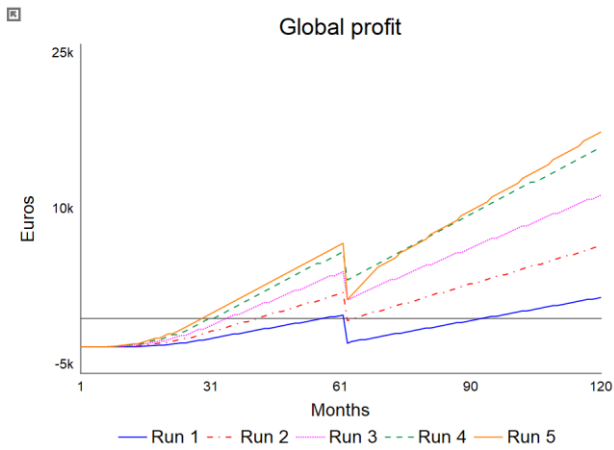


Figure V.45. Printers per school and Global profit
Run 1: 2, Run 2: 3, Run 3: 4, Run 4: 5, Run 5: 6



Figure V.46. Printers per school and Total amount of plastic waste recycled
Run 1: 2, Run 2: 3, Run 3: 4, Run 4: 5, Run 5: 6

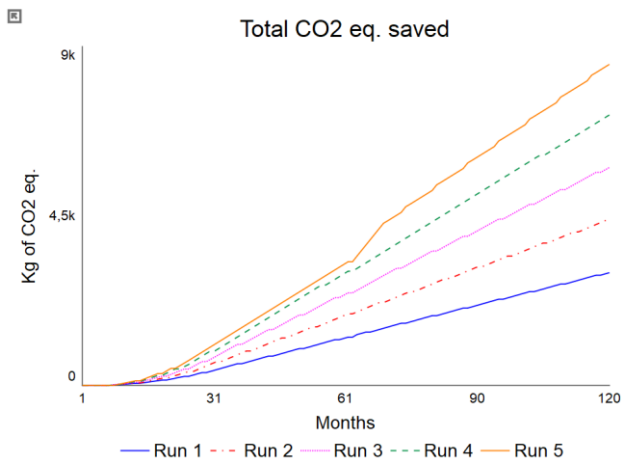


Figure V.47. Printers per school and Total CO₂ eq. saved
Run 1: 2, Run 2: 3, Run 3: 4, Run 4: 5, Run 5: 6

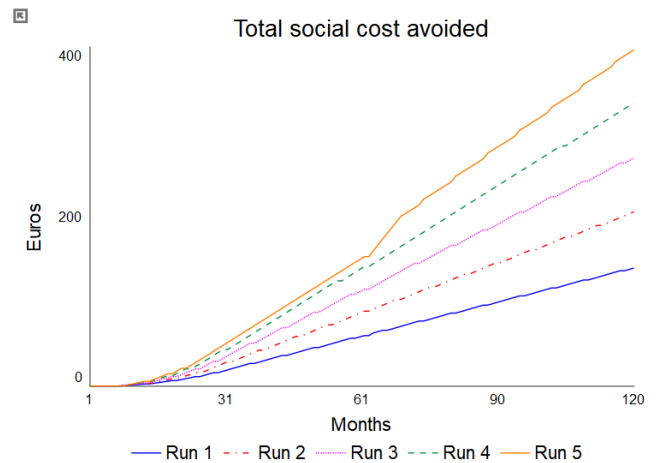


Figure V.48. Printers per school and Total social cost avoided
Run 1: 2, Run 2: 3, Run 3: 4, Run 4: 5, Run 5: 6

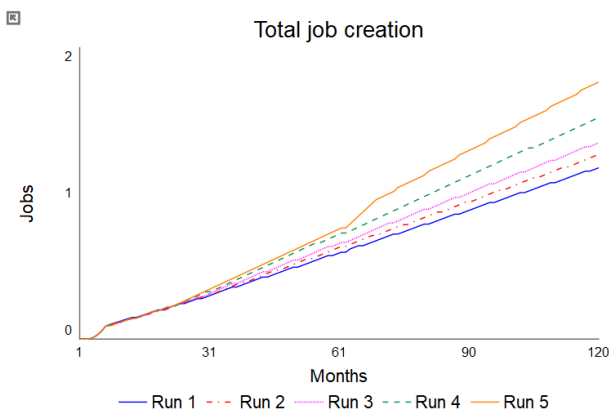


Figure V.49. Printers per school and Total job creation
Run 1: 2, Run 2: 3, Run 3: 4, Run 4: 5, Run 5: 6

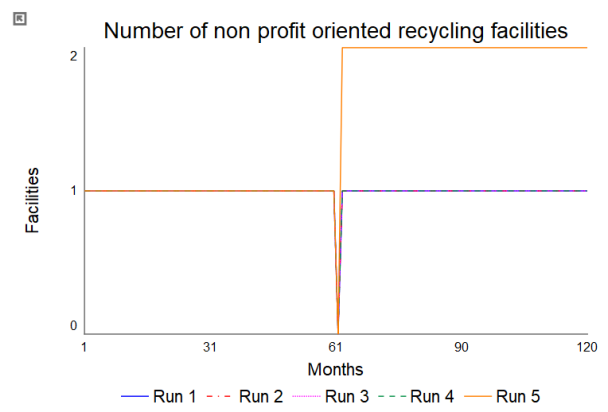


Figure V.50. Printers per school and Number of non-profit oriented facilities
Run 1: 2, Run 2: 3, Run 3: 4, Run 4: 5, Run 5: 6

5.9.6. Scrap rate

This section presents the results obtained from the sensitivity analysis of scrap rate. Figures V.51-56 present the results obtained for each indicator.

The results show a high sensitivity of the indicators to the increase in the scrap rate. An increase in the scrap rate causes a greater availability of waste, which results in the implementation of new facilities and a greater amount of plastic waste recycled. Due to these two facts, an increase is reflected in the other indicators.

5.9.7. Labor cost

This section presents the results obtained from the sensitivity analysis of labor cost. Figures V.57-62 present the results obtained for each indicator.

Variations in the labor cost mainly affect the reinvestment decision. In particular, a cost greater than 19 euros means that a reinvestment is not carried out, causing a break in the indicators around this value. However, considering separately the results for a labor cost lower than 19 euros and those higher than 19 euros, these do not suffer a great variation.

5.9.8. Summary of Sensitivity Analysis

The sensitivity analyses results are summarized in Table V.8. The sensitivity level has been determined by analyzing the variation of the final result against the variation of each parameter. In order to ease the comprehension of the system, the types of sensitivity have been classified as high, medium, low and non-sensitive. A high sensitivity is understood as a curve with a large amplitude or a straight line with a large slope. A medium sensitivity is understood as a curve with a great slope but that at a certain point begins not to vary. A low sensitivity is understood as a curve with a low amplitude or a straight line tending to a flat behavior. Finally, not sensitive is understood as a curve that has no variation. These considerations, will enable to define the scenarios that will be further considered for the recycling system.

Table V.8. Sensitivity analyses results. Degree of sensitivity of the indicators to variations in the input variables.

		OUTPUTS					
		Amount of plastic waste recycled	Global profit	CO ₂ eq. Savings	Social cost avoided	Job creation	Number of recycling facilities
VARIABLES	Price of recycled filament	High	High	High	High	Low	High
	Price of virgin filament	Medium	Medium	Medium	Medium	Low	Medium
	Filament consumption	High	High	High	High	High	Medium
	Investment subsidy	Not sensitive	High	Not sensitive	Not sensitive	Not sensitive	Not sensitive
	Printers per school	High	High	High	High	Low	Low
	Scrap rate	High	High	High	High	High	Medium
	Labor cost per hour	Medium	High	Medium	Medium	Low	Low

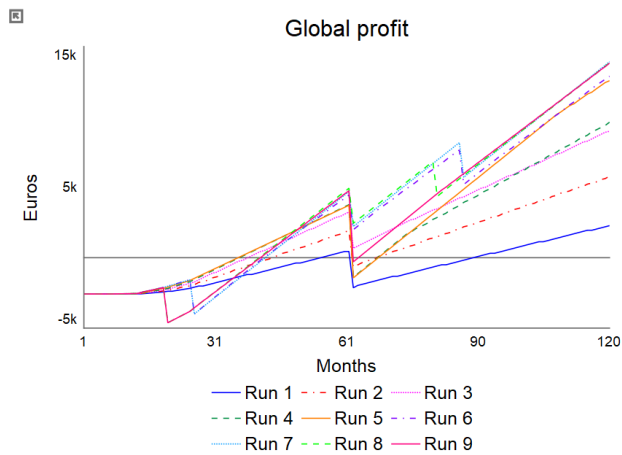


Figure V.51. Scrap rate and Global profit
 Run 1: 0.2, Run 2: 0.3, Run 3: 0.4, Run 4:0.5, Run 5:0.6, Run 6: 0.7, Run 7: 0.8, Run 8: 0.9, Run 9: 1

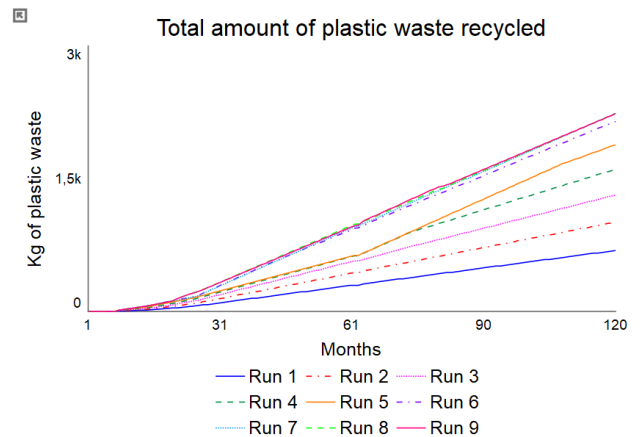


Figure V.52. Scrap rate and Total amount of plastic waste recycled
 Run 1: 0.2, Run 2: 0.3, Run 3: 0.4, Run 4:0.5, Run 5:0.6, Run 6: 0.7, Run 7: 0.8, Run 8: 0.9, Run 9: 1

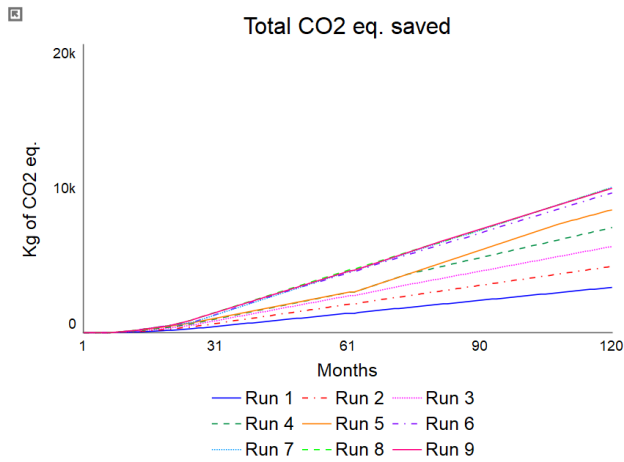


Figure V.53. Scrap rate and Total CO₂ eq. saved
 Run 1: 0.2, Run 2: 0.3, Run 3: 0.4, Run 4:0.5, Run 5:0.6, Run 6: 0.7, Run 7: 0.8, Run 8: 0.9, Run 9: 1



Figure V.54. Scrap rate and Total social cost avoided
 Run 1: 0.2, Run 2: 0.3, Run 3: 0.4, Run 4:0.5, Run 5:0.6, Run 6: 0.7, Run 7: 0.8, Run 8: 0.9, Run 9: 1

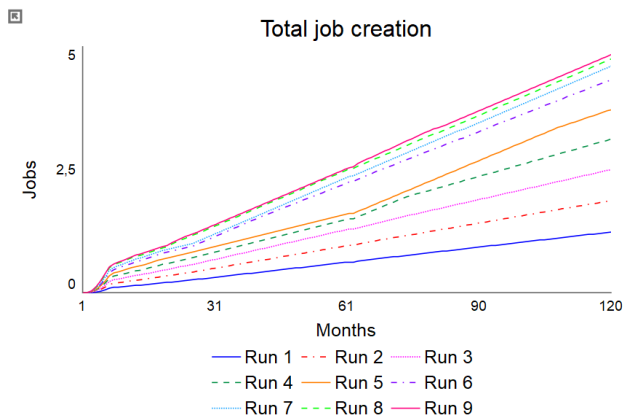


Figure V.55. Scrap rate and Total job creation
 Run 1: 0.2, Run 2: 0.3, Run 3: 0.4, Run 4:0.5, Run 5:0.6, Run 6: 0.7, Run 7: 0.8, Run 8: 0.9, Run 9: 1

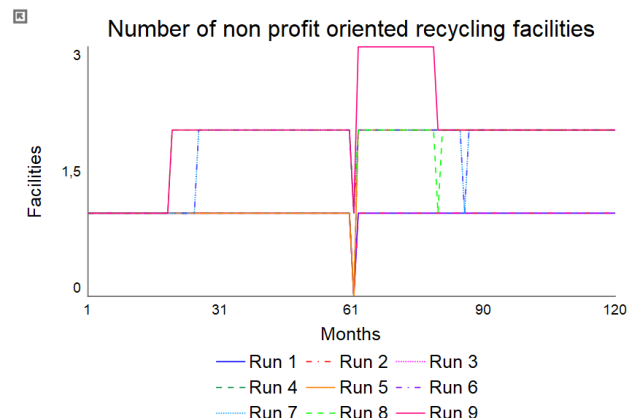


Figure V.56. Scrap rate and Number of non-profit oriented facilities
 Run 1: 0.2, Run 2: 0.3, Run 3: 0.4, Run 4:0.5, Run 5:0.6, Run 6: 0.7, Run 7: 0.8, Run 8: 0.9, Run 9: 1

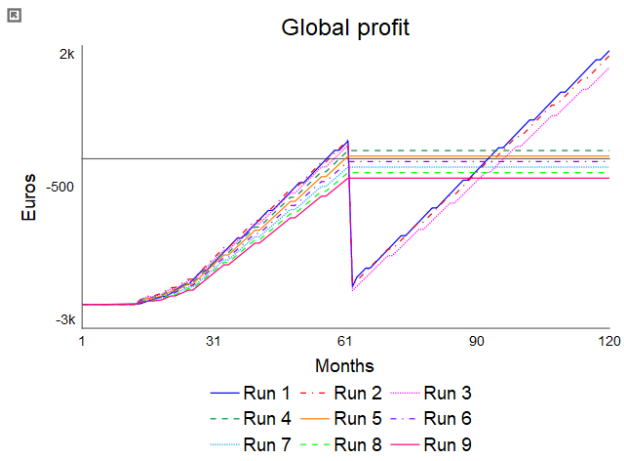


Figure V.57. Labor cost and Global profit
 Run 1: 17, Run 2: 18, Run 3: 19, Run 4: 20, Run 5: 21, Run 6: 22, Run 7: 23, Run 8: 24, Run 9: 25

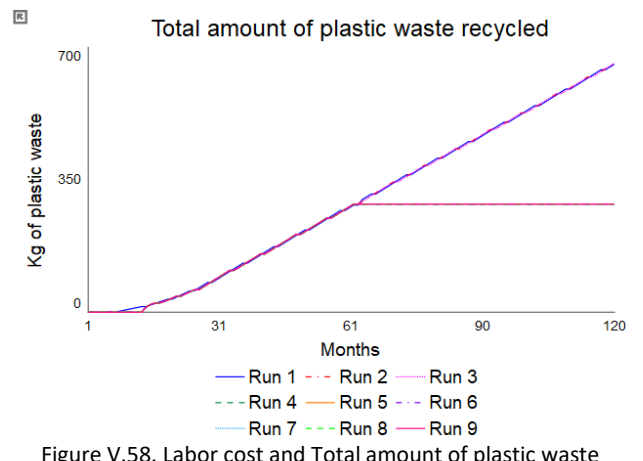


Figure V.58. Labor cost and Total amount of plastic waste recycled
 Run 1: 17, Run 2: 18, Run 3: 19, Run 4: 20, Run 5: 21, Run 6: 22, Run 7: 23, Run 8: 24, Run 9: 25

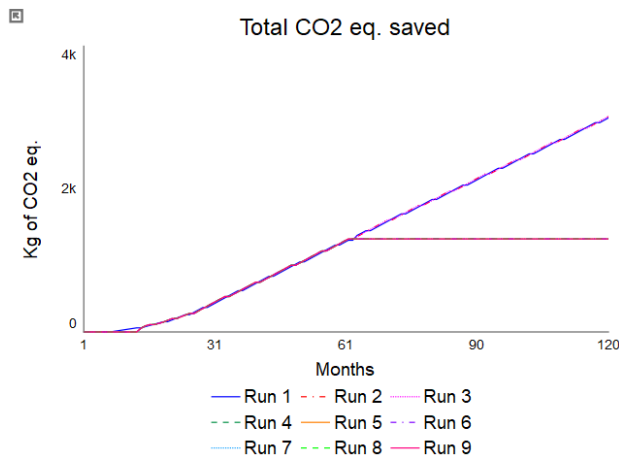


Figure V.59. Labor cost and Total CO₂ eq. saved
Run 1: 17, Run 2: 18, Run 3: 19, Run 4: 20, Run 5: 21, Run 6: 22, Run 7: 23, Run 8: 24, Run 9: 25

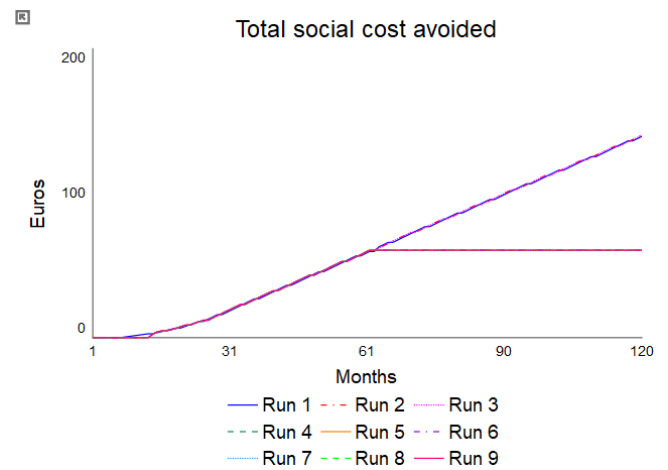


Figure V.60. Labor Cost and Total social cost avoided
Run 1: 17, Run 2: 18, Run 3: 19, Run 4: 20, Run 5: 21, Run 6: 22, Run 7: 23, Run 8: 24, Run 9: 25



Figure V.61. Labor cost and total job creation
Run 1: 17, Run 2: 18, Run 3: 19, Run 4: 20, Run 5: 21, Run 6: 22, Run 7: 23, Run 8: 24, Run 9: 25

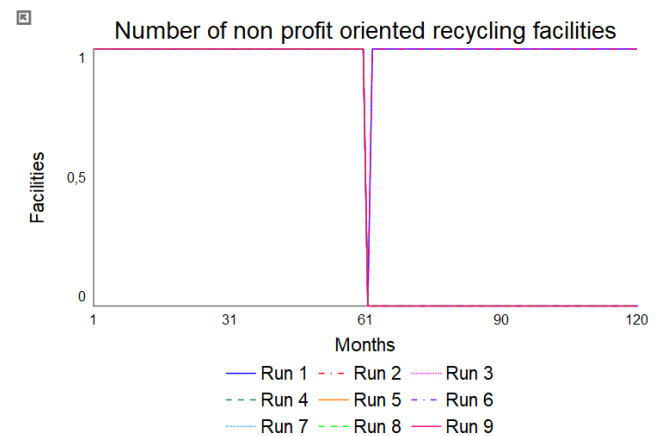


Figure V.62. Labor cost and Number of non-profit oriented facilities
Run 1: 17, Run 2: 18, Run 3: 19, Run 4: 20, Run 5: 21, Run 6: 22, Run 7: 23, Run 8: 24, Run 9: 25

5.10. Scenario Analysis

Based on the results of the sensitivity analysis, those inputs that promote or discourage the development of the distributed plastic recycling are identified. Based on these results, optimistic and pessimistic scenarios are proposed. The input indicators will be increased or reduced simultaneously in each scenario and then, the SD model response will be analyzed.

5.10.1. Optimistic Scenario

In this scenario the simulation condition that promotes the distributed plastic recycling are described in [Table V.9](#). Optimistic scenario considers the following conditions.

- The price of recycled and virgin filament remains unchanged
- Schools and high schools buy 4 printers

- Filament consumption and scrap rate increase due to frequent use of 3D technology in these institutions
- There's a 100% investment subsidy
- The labor cost remains unchanged.

Table V.9. Optimistic scenario condition

Input indicator	Units	Value
Price of recycled filament	Euros/ Kg of filament	20.62
Price of virgin filament	Euros/ Kg of filament	19.99
Filament consumption	Kg of filament / 3D printer	Increase from 0.91 to 2 (linearly)
Scrap rate	%	Increase from 19% to 50% (linearly)
Investment subsidy	Dimensionless	100%
Demand for 3D printers	3D printers/institution	4
Labor cost	Euros/ hour	17

Table IV.10 and Figures V.63-68 show the results obtained for optimistic scenario. As it can be observed, a high global profit (44785.31 euros) is reached in 10 years due to successive investments in new recycling facilities (reaching five facilities). This achieved profit corresponds to more than 20 times the profit achieved in the base scenario (1915.34 euros). The successive investments are due to the high demand of recycled filament (due to the number of printers demanded by the institution and the high consumption of filament) and the high scrap rate due to the use of technology (which causes a high availability of waste). All these factors cause a large amount of plastic waste to be recycled and recycled filament to be manufactured and sold to supply the high demand. The effect of these factors result in 3798.71 kilograms of plastic waste being recycled in 10 years, 18046.89 kg of CO₂ eq. not being emitted, 839.18 euros of social cost being avoided and 4.02 jobs being created. These results are considerably higher than those obtained in the base scenario (655.70 kg of plastic waste, 3996.39 kg of CO₂ eq., 139.33 euros and 1.18 jobs respectively).

Table V.10. Results of optimistic scenario

Year	Global profit (euros)	Total amount of plastic waste recycled (Kg of plastic waste)	CO ₂ not emitted (saved) (Kg of CO ₂ eq.)	Social cost avoided (euros)	Total Job creation (Jobs)	Number of recycling facilities
Year 1	-725.17	19.89	85.48	3.97	0.14	1
Year 2	389.84	115.33	527.19	24.51	0.28	1
Year 3	2983.32	368.30	1731.55	80.52	0.53	2
Year 4	6998.82	661.65	3128.29	145.47	0.83	2
Year 5	11225.65	1033.20	4896.97	227.71	1.20	3
Year 6	16119.08	1453.45	6896.61	320.69	1.62	3
Year 7	22363.53	1909.65	9066.59	421.60	2.08	3
Year 8	28453.11	2480.04	11779.14	547.73	2.66	4
Year 9	36889.58	3096.37	14708.99	683.97	3.30	4
Year 10	44785.31	3798.71	18046.89	839.18	4.02	5



Figure V.63. Global profit of optimistic scenario



Figure V.64. Total amount of plastic waste recycled in optimistic scenario

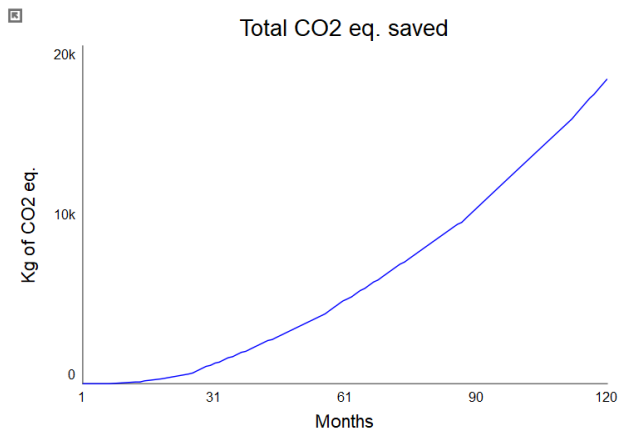


Figure V.65. Total CO₂ eq. saved in optimistic scenario

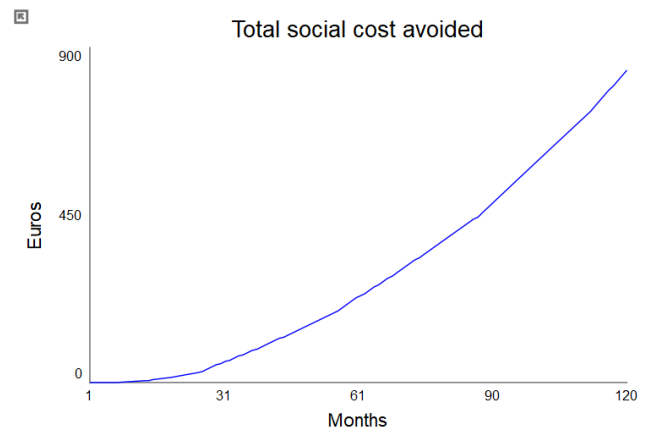


Figure V.66. Total social cost avoided in optimistic scenario

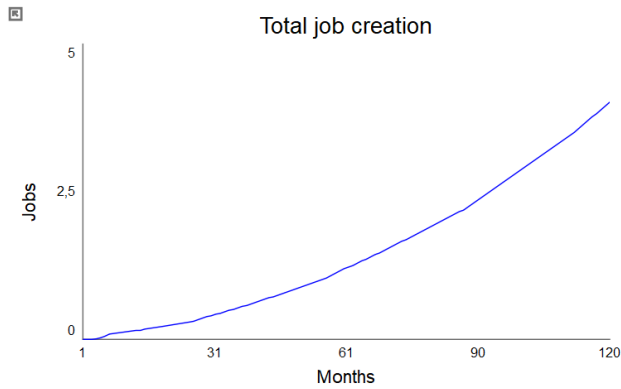


Figure V.67. Total job creation in optimistic scenario

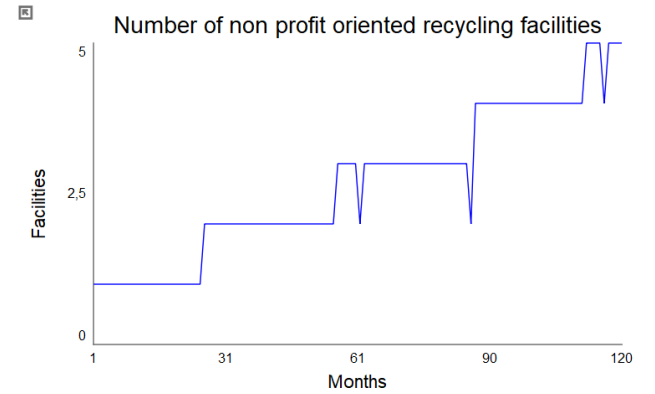


Figure V.68. Number of non-profit recycling facilities in optimistic scenario

5.10.2. Pessimistic Scenario

In this scenario the simulation condition that discourage the distributed plastic recycling are described in [Table V.11](#). Pessimistic scenario considers the following conditions.

- The price of recycled and virgin filament decreases to 10 euros per kilogram of filament
- Schools and high schools buy 2 printers
- Filament consumption and scrap rate remain unchanged
- No subsidy
- The labor cost increases to 20 euros per hour

Table V.11. Pessimistic scenario condition

Input indicator	Units	Value
Price of recycle filament	Euros/ Kg of filament	Decrease from 20.62 to 10 (linearly)
Price of virgin filament	Euros/ Kg of filament	Decrease from 19.99 to 10 (linearly)
Filament consumption	Kg of filament / 3D printer	0.91
Scrap rate	%	19%
Investment subsidy	Dimensionless	Not subsidy
Demand for 3D printers	3D printers/institution	2
Labor cost	Euros/ hour	Increase from 17 to 20 (linearly)

[Table V.12](#) and [Figures V.69-74](#) show the results obtained for the pessimistic scenario. Under this scenario, the demand for recycled filament and virgin filament does not vary too much, since both prices fall in similar values and the demand for filament is assumed inelastic. Therefore, the consumption of filament and the demand for each one hardly varies in this scenario. On the other hand, the decrease in the prices and the increase in the labor cost, causes that the utility obtained to manufacture recycled filament is smaller, which affects directly the obtained profit. Faced with a decrease in the price of recycled filament, the investment is not recovered in 5 years. In addition, the conditions imposed for an investment are not met. Under this scenario, subsidy policies should be applied in order to compensate the obtained negative profit and promote the investment.

Table V.12. Results of pessimistic scenario

Year	Global profit (euros)	Total amount of plastic waste recycled (Kg of plastic waste)	CO ₂ eq. not emitted (saved) (Kg of CO ₂ eq.)	Social cost avoided (euros)	Total Job creation (Jobs)	Number of recycling facilities
Year 1	-2577.00	0.00	0.00	0.23	0.00	1
Year 2	-2239.45	235.44	10.95	0.41	53.84	1
Year 3	-1634.90	562.78	26.17	0.52	125.15	1
Year 4	-1025.98	932.32	43.35	0.64	205.51	1
Year 5	-550.67	1268.28	58.97	0.76	278.56	1
Year 6	-507.03	1301.87	60.54	0.77	285.87	0
Year 7	-507.03	1301.87	60.54	0.77	285.87	0
Year 8	-507.03	1301.87	60.54	0.77	285.87	0
Year 9	-507.03	1301.87	60.54	0.77	285.87	0
Year 10	-507.03	1301.87	60.54	0.77	285.87	0



Figure V.69. Global profit in pessimistic scenario



Figure V.70. Total amount of plastic waste recycled in pessimistic scenario

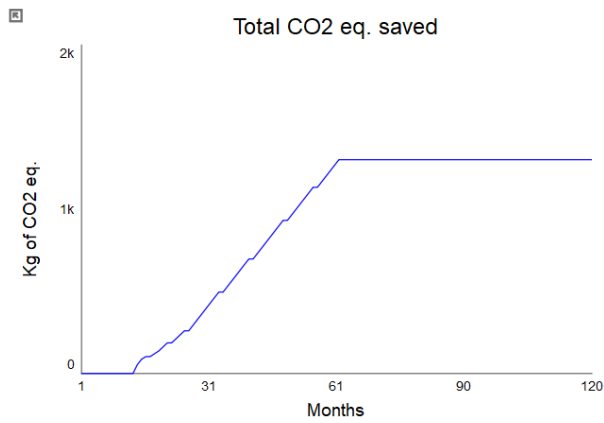


Figure V.71. Total CO₂ eq. saved in pessimistic scenario

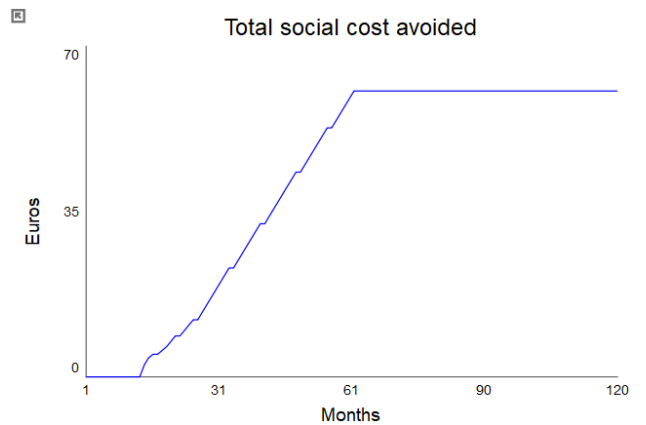


Figure V.72. Total social cost avoided in pessimistic scenario

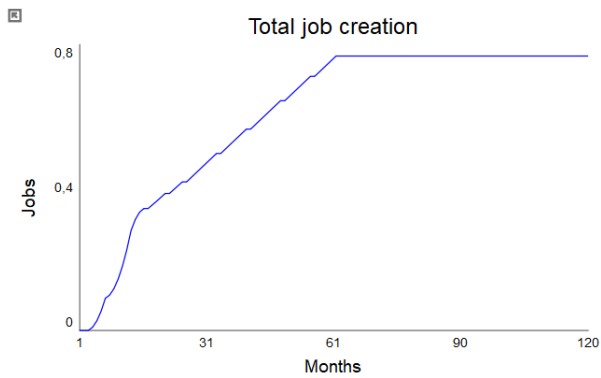


Figure V.73. Total job creation in pessimistic scenario

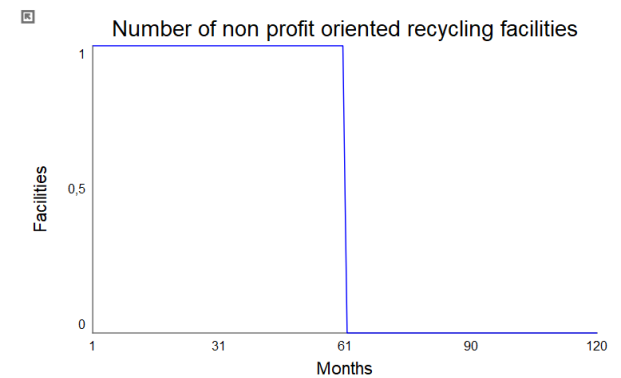


Figure V.74. Number of non-profit oriented facilities in pessimistic scenario

5.11. Discussion

In this chapter, the systems dynamics approach has been applied to study the conditions for the development of distributed plastic recycling from a sustainable point of view.

The results of the case study application demonstrate the economic, environmental and social benefits of distributed plastic recycling in reduced volumes. From the economic point of view, the results have shown that the investment is recovered in less than 5 years, obtaining a global profit of 239.65 euros. Indeed, if a reinvestment is made, the global profit could reach 1 782.77 euros. It is worth mentioning that the investment needed to implement a recycling facility is less than 3 000 euros (Granulator and extruder). Considering the environmental indicators, the results show that a total of 648.44 kg of plastic waste would be recycled by the system in 10 years and that a total of 3015.20 kg of CO₂ eq. would be avoided due to the recycling process. From the social point of view, a social cost equivalent to 140.21 euros would be avoided in 10 years. All these results could be achieved with just one small plastic recycling facility. Based on a sensitivity analysis, pessimistic and optimistic scenarios have been proposed. The analysis of these scenarios shows the high dependency of the system on plastic waste generation and the price of the recycled filament. In particular, both scenarios show the importance of a subsidy to enhance the development of this recycling approach. Regardless of the scenario, a subsidy decreases the investment and promotes the implementation of recycling facilities, so more plastic waste could be recycled. On the other hand, the high dependency of the system on plastic waste generation, makes it necessary to consider other sources of 3D printing waste (not only educational institutions), which could increase the benefits obtained.

The obtained results in this research, motivate the application of this model in other territories. However, the model developed is limited to 3D printing waste and only considers two actors: educational institutions (3D printing users) and non-profit organizations (recycled filament suppliers). 3D printing is a developing technology whose use will probably increase due to, for example, distributed manufacturing. Considering this, the results of this research motivate the integration, in future research, of other participating actors in the context of 3D printing and distributed plastic recycling. For example, particular users of 3D printing and for-profit organizations to perform the recycling process.

5.12. Summary

In this document, a system dynamics model has been developed for the sustainability evaluation of distributed plastic recycling.

The model has been applied to the case of Lorraine Fab Living Lab for the implementation of a closed plastic recycling circuit for 3D printing waste from schools and high schools in Nancy. The results show the economic, environmental and social benefits of plastic recycling in small quantities.

As actors of the system, the model only considers as users of 3D printing educational institutions, and as recycled filament suppliers, only considers non-profit organizations. Future research might consider the integration of other actors, either by the part of 3D printing users (other types of institutions or prosumers) or by recycled suppliers (for-profit recycling facilities). An important limitation of the model developed is the simulation of the demand for recycled filament and the criteria for the implementation of recycling facilities. Future research could study the decision of these actors.

On the one hand, in the case of 3D printing users, the decision of consumers regarding the purchase and use of recycled filament could be studied. In this model consumer demand has been simulated in terms of price and performance by comparing virgin and recycled filament. However, other types of consumer sensitivities that determine demand could be explored, for example, environmental awareness. Another aspect to consider from the consumer's point of view is the scrap rate. The sensitivity analysis conducted assumes an increase in filament consumption and scrap rate due to more frequent use of the technology. However, factors such as consumer learning in the use of 3D printing could be considered, which could have effects on the scrap rate over time. On the other hand, in the case of recycling facilities, the decision criteria for the implementation of facilities (profit or non-profit) could be studied. It should also be mentioned that the model developed considers only one material, so future research could extend the model to consider multiple types of plastic waste. Finally, from the technological point of view, this system has been modeled for 3D printers that use plastic filament to make the prints. However, currently the printing by means of direct extrusion (printing by means of pellets, without the need of filament) is in development [248]. This type of technology impacts the developed system in different ways. First, from the investment point of view, the recycling points would not have to invest in an extrusion machine, since it would be possible to print directly from shredded plastic. From the cost point of view, the recycling process could have a lower cost from the operational point of view, since the extrusion process for the filament fabrication would be avoided. Finally, from the technical point of view, not needing an extrusion to fabricate filament, would mean that the recycled plastic would have a smaller loss of properties in each recycling cycle. Therefore, greater recyclability in the system could be considered for those plastics that have already been recycled.

Chapter VI. Conclusions and perspectives

The development of 3D printing has led the emergence within the scientific community of a new paradigm of plastic recycling called distributed recycling. The technical feasibility of this paradigm has been conceptualized in literature. However, its feasibility from the logistic/supply chain point of view remained unproven. In this research thesis, this issue has been addressed by proposing a methodological framework for the evaluation of distributed plastic recycling for 3D printing. This methodological framework has been proposed in order to answer the following research question: Under which conditions is it possible to deploy a sustainable local and distributed plastic recycling network using open source 3D printing technologies?

In the first chapter, a literature review has been conducted in order to explore the plastic recycling paradigms studied in the literature, as well as their methodologies and evaluation criteria. The results of this literature review correspond to the first contribution of this thesis. Specifically, results of the literature review have shown that, in the context of plastic recycling, the distributed recycling paradigm has not yet been addressed from the network point of view. Therefore, this work corresponds to the first to address this paradigm, which, according to the literature background, could be carried out using 3D printing technology. From the point of view of evaluation, the plastic recycling networks has been evaluated mainly considering economic and environmental aspects, where social, technological and political aspects of sustainability have been scarcely considered. Finally, as evaluation tools, the optimization approach has been the most considered.

Based on the results obtained in the first chapter, in the second chapter we have explored how social, technological and political aspects should be considered for a more holistic evaluation of recycling networks from a sustainability point of view. As a result of the literature review, a set of criteria and indicators for social, technological and political dimensions have been extracted for this and others evaluations. This corresponds to the second contribution of this thesis.

Then, in the third chapter, a two-level framework has been proposed to be used in this and other evaluations of distributed recycling approaches. With the proposed evaluation framework, the system here studied can be evaluated from the sustainability point of view, considering at the same time the complexities present in it. This evaluation framework, corresponds to the third contribution of this thesis. Specifically, the modeling approach proposes an analysis from the system point of view (upper layer) and from the operational point of view (lower layer). System Dynamics and Mathematical Optimization have been proposed as methodologies for the upper and lower layer respectively. System dynamics has been proposed in order to consider qualitative aspects that are not possible to consider by means of optimization models.

In the fourth chapter the optimization model proposed for the evaluation of the distributed recycling of plastic from the logistic point of view has been presented. This model corresponds to the fourth contribution of this thesis, being the first formalization, from the logistic point of view, of the distributed plastic recycling using the 3D printing technology. The application of the model to a specific case study of the Lorraine Fab Living Lab, France, has shown the economic and environmental benefits obtained from carrying out the activity.

In the fifth chapter, the analysis has been extended based on a system dynamic model developed for the evaluation, from the sustainability point of view, of the distributed recycling of plastic using 3D printing. The model developed corresponds to the fifth contribution of this thesis, formalizing this recycling approach from the system point of view. The application of the model to the same case study

of the Lorraine Fab Living Lab (France), has shown the economic, environmental and social benefits obtained by carrying out this recycling approach.

In conclusion, this research thesis has explored the feasibility of distributed plastic recycling by simultaneously integrating sustainability dimensions (based on the TBL+ approach) and through a specific case study. The results of the application of the proposed methodology (based on optimization and system dynamics) have shown their relevance for the design of local plastic recycling networks. The potential of such a network resides in the current and future diffusion of 3D printing. The models developed can also be used to assist in logistical and implementation decisions during the sustainability evaluation of this recycling approach.

8.1. Limitations and perspectives

As this is the first research work to address distributed plastic recycling from a logistic/supply chain and sustainability point of view, it is difficult to consider all the complexities and aspects of the problem. Here, some limitations to this contribution will be highlighted in order to shed some light on the future work that could derive from it.

1. Considering the used methodologies (systems dynamics and optimization), these methodologies have been used with the following limitations. On the one hand, in the case of systems dynamics, the model has been constructed to consider only two actors in the system (Non profit oriented recycling facilities and Schools). In addition, the system only considers one material (only one specific 3D printing waste). Therefore, future research could consider other possible actors that could participate in the studied system (e.g. profit oriented recycling facilities and private 3D printing users). Also, future work could consider different types and sources of waste and mix of materials, which in turn implies considering other complexities of the process (sorting, cleaning, and decontamination). Finally, considering the relationships between the elements, some of them have been taken as assumption. For example, the demand for recycled filament and decisions to implement recycling facilities have been estimated based on our previous experiences but still to be proven at real scale. Therefore, future research could address consumer behavior of recycled filament, as well as aspects that would motivate the implementation of local plastic recycling networks. On the other hand, for the case of the developed optimization model, the model corresponds to a single objective, a single period, a single type of material and considers only the maximization of economic and environmental aspects (in a single objective function). Future research could develop more robust models that consider different sustainability criteria (established in this research) in different objective functions. In this way, objectives of different decision makers could be considered. Also, future research could extend the model to consider more than one material at the same time and more than one period (multi-period model).
2. From an evaluation point of view, the impact of this recycling approach on ecosystem services has not been considered. The negative impact that plastic waste has on biodiversity (especially in the sea) and on human health due to the additives used in its production is well known. Therefore, the avoided (or unavoidable) impact on ecosystem services due to this recycling approach would be an evaluation for future research.

3. Considering the evaluation framework proposed in this research, it has been used in only one way. Specifically, the operational layer has been explored first, where the results obtained have been used in the system layer (see Fig VI.1). This mode of use has been mainly due to the availability of data, where thanks to the optimization model developed and its application to the case study, operational data have been obtained to be used in the same case study at the system level. However, in case of more data availability, the application of this evaluation framework could be carried out in a reverse way. For example, the sensitivity analyses conducted for the optimization model allows for analysis of the model's behavior under different scenarios. In turn, these scenarios are posed due to the system's dependence with other elements (political context, technology development, etc.), which could be integrated by means of systems dynamics. Therefore, scenarios could be posed through the application of systems dynamics, which could be analyzed through optimization models. Also, this evaluation framework could be used in an iterative way alternating each methodology. In conclusion, the experience obtained with this research has allowed us to conclude that the way in that the methodology should be applied depends on the availability of data, as well as the profile of the modeler (systemic profile, operational profile or both). Therefore, a standard (but adapted to the needs of the modeler) way of applying both methodologies in the supply chains evaluation could be addressed in future research.

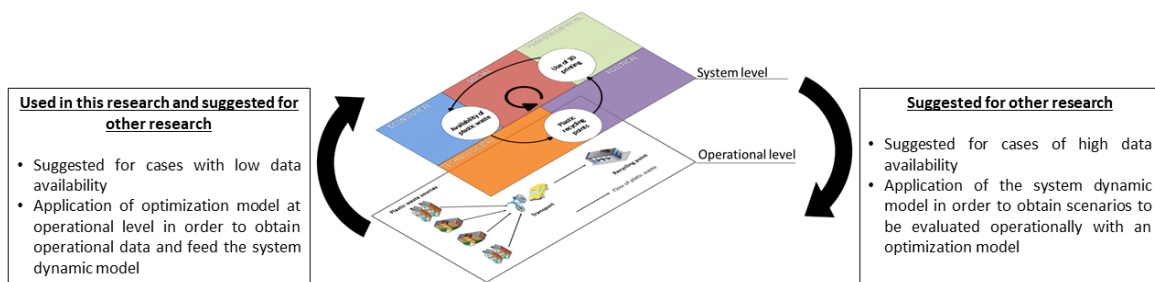


Figure VI.1. Proposed integration of systems dynamics and optimization for supply chains evaluation.

4. From the point of view of application, the application and feasibility of this recycling approach may vary due to the context of application (citizens' behavior, policies, etc). In order to analyze this, future research could apply this methodology in different territories in order to analyze the feasibility of this recycling approach in different contexts.
5. If we consider the proposed scheme Fig 0.1, we have by now considered only more less clean “plastic waste”. An important work have to be done on the preparation phases (Fig 0.1) in order to allow a more important local recycling from plastic waste.

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Appendix Chapter I.

Appendix I.1. Sustainability dimensions for plastic recycling network

Table 26. Economic criteria identified in the literature on the evaluation of plastic recycling networks

Dimension	Criteria	Number of documents	References
Economical Dimension	Cost of transport/shipping	29	[10], [50]–[52], [54], [57]–[62], [65], [67]–[73], [82], [84]–[87], [90]–[92], [106]
	Cost of recovery	2	[62], [69]
	Cost of compression	1	[69]
	Cost of pretreatment	1	[69]
	Cost of recycling	9	[50], [53], [54], [58], [59], [67], [69], [72], [84]
	Cost of distribution	4	[53], [54], [58], [69]
	Collection cost	14	[50], [54], [58], [61]–[63], [65], [67], [70], [73], [78], [86], [88], [106]
	Opening cost	12	[52], [57], [59], [60], [62], [67], [68], [70], [72], [82], [86], [87]
	Carbon cost	1	[70]
	Cost of inspection	3	[55], [63], [71]
	Cost of dismantling	1	[71]
	Cost of fabrication/production/ Manufacturing	10	[51]–[54], [58]–[60], [62], [71], [92]
	Cost of disposal	6	[54], [58], [59], [63], [71], [92]
	Hiring cost	1	[71]
	Revenues	9	[52], [55], [58], [60], [63], [64], [68], [71], [86]
	Cost of supplier	1	[58]
	Cost per unit recycled	1	[75]
	Closing cost	1	[72]
	Setup cost	2	[65], [84]
	Inventory cost	6	[56], [59], [61], [84], [86], [90]
	Material cost	2	[56], [59]
	Remanufacturing cost	1	[59]
	Disassembly cost	2	[51], [59]
	Repairing cost	1	[59]
	Shortage cost	1	[59]
	Non-utilized capacity cost	1	[59]
	Cost savings due to product recovery	2	[52], [60]
	Labor cost	3	[56], [81], [91]
	Real-estate rental cost	1	[56]
	Land rehabilitation cost	1	[56]
	Penalty cost for damage to the environment	1	[56]
	Unitary profit	1	[82]
	Disposal tax per unit of residual product	1	[82]
	Processing cost	8	[57], [61], [62], [83], [86], [87], [92], [106]
	Investment	2	[63], [81]
	Sorting cost	2	[62], [92]
	Economic value added	1	[249]
	Return on investment	1	[76]
	Cost of freight	1	[78]
	Cost of handling	3	[73], [90], [106]
Cost of trading emissions	1	[106]	
Holding cost	2	[51], [65]	
Costs of the packaging	2	[80], [90]	
Costs of the reverse chain	1	[80]	
Internal costs of the forward chain	1	[80]	
Cost of incorporating sustainability features	1	[55]	
Operation/management cost of the facility	2	[65], [83]	
Acquisition costs	1	[90]	
Container cost	1	[91]	
Damage cost	1	[91]	
Quality	1	[74]	

Table 26. Economic criteria identified in the literature on the evaluation of plastic recycling networks (continuation)

Dimension	Criteria	Number of documents	References
Economical Dimension	Cost	1	[74]
	Lead time	1	[74]
	Delivery	1	[74]
	Experience	1	[74]
	Transport	1	[74]
	Services	1	[74]
	Technical innovation	1	[74]
	Waste product repair cost	1	[74]
	Second-hand product fixed cost of sale	1	[89]
	Distance travelled	1	[89]
	Internal rate of return	1	[93]
	Net present value	1	[93]
	Incentive cost	1	[87]
	Production flexibility	1	[77]
	Delivery cost	1	[77]
	Investment in sustainability design	1	[77]
	Time delivery	1	[77]
	Supplier rejection rate	1	[77]
	Service quality	1	[77]
	Fixed cost of vehicle	1	[88]
Energy cost	1	[81]	
Water cost	1	[81]	
Building cost	1	[81]	

Table 27. Environmental criteria identified in the literature on the evaluation of plastic recycling networks

Dimension	Criteria	Number of documents	References
Environmental Dimension	Carbon emissions	6	[10], [50]–[52], [54], [57]–[62], [65], [67]–[73], [82], [84]–[87], [90]–[92], [106]
	Emissions of CO ₂ / CO ₂ eq	15	[10], [50], [54], [69], [71], [73], [78], [94]–[97], [99], [102], [103], [249]
	Volume of material no discarded	1	[75]
	Recycled Plastic target	1	[72]
	Cost of land use	1	[56]
	Cost of land rehabilitation	1	[56]
	Penalty for damage to the environment	1	[56]
	Energy	6	[50], [81], [95]–[97], [99]
	Water	7	[76], [81], [95], [96], [98], [101], [102]
	Effluents	1	[95]
	Solid waste	2	[95], [97]
	Landfill increased usage life	2	[102], [249]
	Abiotic Goods	3	[76], [98], [101]
	Biotic Goods	3	[76], [98], [101]
	Air	3	[76], [98], [101]
	Green design	1	[51]
	Climate change	1	[96]
	Ozone depletion	3	[80], [96], [97]
	Human toxicity	2	[80], [96]
	Photochemical oxidant formation	1	[96]
	Particulate matter formation	1	[96]
	Ionizing radiation	1	[96]
	Terrestrial acidification	2	[96], [102]
	Freshwater eutrophication	1	[96]
	Marine eutrophication	2	[96], [102]
	Terrestrial ecotoxicity	1	[96]
	Freshwater ecotoxicity	1	[96]
Marine ecotoxicity	2	[96], [102]	
Agricultural land occupation	1	[96]	
Urban land occupation	1	[96]	

Table 27. Environmental criteria identified in the literature on the evaluation of plastic recycling networks (continuation)

Dimension	Factor	Number of documents	References
Environmental Dimension	Natural land transformation	1	[96]
	Metal depletion	1	[96]
	Fossil depletion	1	[96]
	CO	1	[96]
	PM	2	[96], [102]
	NOX	1	[96]
	NMVOG	1	[96]
	Greenhouse effect	1	[80]
	Acidification	2	[80], [97]
	Nutrition	1	[80]
	Human Health Criteria Air-Point Source (mg PM10-eq)	1	[97]
	Photochem. Ozone Creation Potential (mg C2H4-eq)	1	[97]
	Eutrophication Potential (mg P-eq)	1	[97]
	Eutrophication Potential (mg N-eq)	1	[97]
	Fossil resource scarcity	1	[102]
	Environmental Impact	2	[67], [100]
	Recycle	1	[74]
	Reuse	1	[74]
	Remanufacture	1	[74]
	Eco-design production	1	[74]
	Green design	1	[74]
	Amount of pollution	1	[77]
ISO 14001 certification	1	[77]	
Hazardous materials	1	[77]	
Number of green products	1	[77]	

Table 28. Social criteria identified in the literature on the evaluation of plastic recycling networks

Dimension	Criteria	Number of documents	References
Social Dimension	Profit for the contracted company	1	[75]
	Obnoxious effects	1	[82]
	Customer's sensitivity	3	[55], [63], [64]
	Degree of CSR	1	[63]
	Incentive for returned product	1	[57]
	Income generation	1	[249]
	Employees training	1	[76]
	Social behavior for disposal and recycling product	1	[50]
	Service level to customers	1	[67]
	Inclusion of waste pickers	1	[68]
	PW recovery per-capita	1	[94]
	Health and safety	2	[74], [77]
	Voice of customer	1	[74]
	Customers satisfaction	1	[77]
	Workload of facilities	1	[89]

Table 29. Political criteria identified in the literature on the evaluation of plastic recycling networks

Dimension	Criteria	Number of documents	References
Political Dimension	Imposition of the RL network	1	[78]
	Emission quota	1	[106]
	Emission cap	1	[106]
	Penalty cost by use of plastic in packaging	1	[51]
	Incorporation of Governmental collection center	1	[55]
	Imposition of reduction rate and selling price of product	1	[55]
	Governmental support for one unit of WEEE	1	[83]
	Legal context	1	[50]
	Flux Conditions of waste policy	1	[68]
	Inclusion of waste pickers associations	1	[68]
	Disposal tax per unit of residual product	1	[82]
	Respect for the local rules and policies	1	[74]

Table 30. Technological criteria identified in the literature on the evaluation of plastic recycling networks

Dimension	Criteria	Number of documents	References
Technological dimension	Capacity of facilities	25	[50]–[54], [57]–[62], [65], [67]–[72], [82]–[87], [94]
	Recycling Technique	1	[69]
	Capacity of transport	12	[57], [58], [65], [67], [71], [72], [85]–[88], [94], [95]
	Recycling rate	2	[58], [59]
	Desired plastic waste target	1	[72]
	Capacity of machine	1	[72]
	Technology selection	2	[10], [82]
	Processing time	2	[61], [83]
	Quality of returned product	1	[57]
	Recovery service rate	1	[62]
	Quality of products	1	[51]
	Recovery options	2	[96], [249]
	Modality selection	1	[73]
	Availability of the necessary technology	1	[50]
	Sells options of discarded product	1	[50]
	Means of transport for waste	1	[50]
	New technology implementation	1	[94]
Recovery ratio	1	[53]	
Conversion coefficient	1	[53]	

Appendix Chapter II.

Appendix II.1. Workers-oriented social criteria

Table 31. Workers-oriented social criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Job creation or employment	Quantitative	Number of created jobs (opportunities) opening facilities	Multi-Criteria and Optimization	E-waste	1	[116]
			Optimization	Construction and demolition wastes	1	[138]
				General	2	[144], [146]
				Glass	1	[147]
				Light bulbs	1	[150]
				Medical waste	1	[152]
				Tire	1	[46]
		Scenario analysis and quantification	Biorefinery	1	[169]	
		Variable job creation per product	Multi-Criteria and Optimization	E-waste	1	[116]
			Optimization	General	2	[144], [146]
	Glass			1	[147]	
	System Dynamics		Gold from cellphones	1	[11]	
	Employment score of facilities	Optimization	E-waste	2	[139], [141]	
	Number of formal e-waste workers	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]	
Increase/decrease of qualified/non-qualified labor force of opening/close facilities	Optimization	E-waste	1	[142]		
Number of people targeted to be employed at facility	Optimization	E-waste	1	[119]		
Unemployed people	System Dynamics	E-waste	1	[126]		
Qualitative	Relative weight Social performance criteria	Multi-Criteria decision making	End of life vehicles	1	[133]	
Safety of worker	Quantitative	Lost days	Optimization	Light bulbs	1	[150]
		Lost days		Tire	1	[46]
		Number of employees who work under safe conditions		Plastic	1	[77]
	Qualitative	Relative weight of Health and safety criteria	Multi-Criteria and Optimization	E-waste	1	[117]
		Relative weight of Health and safety criteria		Plastic	1	[74]
		Relative weight of Health and safety criteria		End of life vehicles	2	[133], [134]
		Relative weight of Health and safety criteria		Light bulbs	1	[136]
		Relative weight of Health risks and working conditions criteria		Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1
	No indicator	Without indicator	Multi-Criteria and Optimization	E-waste	1	[116]

Table 31. Workers-oriented social criteria (continuation)

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference	
Health of workers	Quantitative	Number of employees who work under safe conditions	Hybrid BSC-DEA (balanced scorecard - data envelopment analysis)	Plastic	1	[77]	
		Lost days	Optimization	Light bulbs	1	[150]	
	Qualitative	Relative weight of Health and safety criteria		Multi-Criteria and Optimization	E-waste	1	[117]
					Plastic	1	[74]
		Relative weight of Health risks and working conditions criteria		Multi-Criteria decision making	End of life vehicles	2	[133], [134]
					Light bulbs	1	[136]
		Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]		
Damage to workers	Quantitative	Lost days	Optimization	Construction and demolition wastes	1	[138]	
				General	1	[144]	
				Glass	1	[147]	
				Medical waste	1	[152]	
				Tire	1	[46]	
		Damage to workers score of facilities	Optimization	E-waste	2	[139], [141]	
Employment Practices	Qualitative	Relative weight of Employment Practices criteria	Multi-Criteria decision making	E-waste	1	[118]	
				Light bulbs	1	[136]	
		Relative weight Equity labor sources criteria	Multi-Criteria and Optimization	E-waste	1	[117]	
		Relative weight Staff training criteria	Multi-Criteria and Optimization	E-waste	1	[117]	
		Relative weight of Employee training criteria	Multi-Criteria decision making	End of life vehicles	1	[134]	
	Relative weight of Employment opportunities & job satisfaction criteria	Multi-Criteria decision making	End of life vehicles	1	[134]		
No indicator	Without indicator	Qualitative analysis	General	1	[168]		
Employment stability	Qualitative	Relative weight of Employment stability criteria	Multi-Criteria and Optimization	Plastic	1	[74]	
				Multi-Criteria decision making	E-waste	1	[165]
		Relative weight Employee turnover rate criteria	Multi-Criteria decision making	General	1	[166]	
		Likert scale of Employment Stability criteria	Statistical analysis	E-waste	1	[158]	
	No indicator	Without indicator	Qualitative analysis	General	1	[168]	
Job satisfaction	Quantitative	Amount of job satisfaction created by employee support	Optimization	Light bulbs	1	[150]	
	Qualitative	Relative weight of Employment opportunities & job satisfaction criteria	Multi-Criteria decision making	End of life vehicles	1	[134]	
Employee benefits	Qualitative	Relative weight of Employee Benefit criteria	Multi-Criteria decision making	E-waste	1	[165]	
		Likert scale of Employee Benefit criteria	Statistical analysis	E-waste	1	[158]	
Access to education	Quantitative	Number of e-waste workers and relatives with high level of education	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]	
Access to healthcare	Quantitative	Number of e-waste workers and their relatives provided with health insurance	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]	
Total employee fund generated	Quantitative	Fund allocation per employee	Multi-Criteria and Optimization	E-waste	1	[156]	
Establishment of new employment opportunities	Quantitative	Number of drivers hired for transportation	Multi-Criteria and Optimization	E-waste	1	[116]	
Training and education to employees	Quantitative	Training hours for skilled staff	Multi-Criteria and Optimization	E-waste	1	[116]	
Working hours	Quantitative	Total hour of work per worker	System Dynamics	E-waste	1	[140]	
Flexible working arrangements	Qualitative	Relative weight of flexible working arrangements criteria	Multi-Criteria and Optimization	Plastic	1	[74]	

Table 31. Workers-oriented social criteria (continuation)

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Labor equity and supplier stock management	Qualitative	Relative weight of labor equity and supplier stock management criteria	Multi-Criteria and Optimization	Plastic	1	[74]
Workers status	No indicator	Without indicator	Discounted cash flow	Municipal solid waste	1	[111]
Human capital	No indicator	Without indicator	Qualitative analysis	General	1	[168]

Appendix II.2. Customer-oriented social criteria

Table 32. Customer-oriented social criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Consumers' preference	Quantitative	Degree of preference (Number between 0 and 1)	Game theory	General	3	[114], [154], [155]
	No Indicator	Without indicator	Optimization	Kitchenware	1	[149]
Incentives to customers	Quantitative	Offered acquisition prices to customer	Game theory	General	1	[164]
			Optimization	General	1	[143]
		Variational inequality	General	1	[128]	
Safety of consumer	Quantitative	Percentage of product	System Dynamics	Gold from cellphones	1	[128]
	Quantitative	Fraction of potentially perilous products	Optimization	Light bulbs	1	[150]
Health of customer	Qualitative	Relative weight of Health and safety criteria	Multi-Criteria decision making	E-waste	2	[118], [165]
	Qualitative	Likert scale of Health and safety criteria	Statistical analysis	E-waste	1	[158]
Sensitivity of the customers	Quantitative	Fraction of potentially perilous products	Optimization	Light bulbs	1	[150]
	Qualitative	Relative weight of Health and safety criteria	Multi-Criteria decision making	E-waste	2	[165] [118]
Consumer behavior for disposal and recycling product	Qualitative	Likert scale of Health and safety criteria	Statistical analysis	E-waste	1	[158]
	No Indicator	Without indicator	Game theory	E-waste	1	[112]
Participation rate	Quantitative	Function of incentive rate	Optimization	General	3	[55], [129], [130]
			PESTLE analysis	Plastic	1	[50]
Product harming the customers	Quantitative	Percentage of the products harming the customers	Qualitative analysis	Tire	1	[157]
			Optimization	Biomass	1	[167]
Accessibility and responsiveness to customers	Quantitative	Distances from the facilities/distributors to the customers	Optimization	General	1	[144]
Service level	Quantitative	Amount of product transported to customer	Optimization and LCA	General	1	[145]
Voice of customer	Qualitative	Relative weight of Voice of customer criteria	Optimization and LCA	Plastic	1	[67]
Firm's service quality	Qualitative	Relative weight of Voice of customer criteria	Multi-Criteria and Optimization	Plastic	1	[74]
Public engagement	Qualitative	Likert Scale of Improve our firm's service quality criteria	Statistical analysis	General	1	[170]
Public engagement	No Indicator	Without indicator	Qualitative analysis	Photovoltaic technologies	1	[123]

Appendix II.3. Community-oriented social criteria

Table 33. Community-oriented social criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Donation to community	Quantitative	Monetary amount for per unit sells	Game theory	General	1	[163]
		NGO fund allocation	Multi-Criteria and Optimization	E-waste	1	[156]
	Qualitative	Relative weight of Donation to community criteria	Multi-Criteria decision making	E-waste	1	[165]
		Likert scale of Donation to community criteria	Statistical analysis	E-waste	1	[158]
Corporate social responsibility	Quantitative	Fraction of CSR	Game theory	Plastic, glass and metal	1	[63]
	Qualitative	Degree of CSR (Corporate social responsibility)	Game theory	Batteries	1	[127]
		Relative weight of Corporate social responsibility criteria	Multi-Criteria decision making	E-waste	1	[161]
Inclusion of waste pickers	Quantitative	Formalization rate	System Dynamics	E-waste	1	[135]
	No indicator	Without indicator	Discounted cash flow	Municipal solid waste	1	[111]
			Optimization	Municipal solid waste	1	[68]
Social Cost of Carbon	Quantitative	Estimate of the damages associated with a small increase in carbon dioxide emissions	Optimization	Municipal solid waste	1	[153]
		Cost of emitting one extra ton of carbon	Optimization	Tire	1	[179]
Local community influence	Qualitative	Relative weight Local community influence criteria	Multi-Criteria and Optimization	E-waste	1	[117]
Local development	Qualitative	Local development score of facilities	Multi-Criteria decision making	Light bulbs	1	[136]
			Optimization	E-waste	2	[139], [141]
Community complaints	Qualitative	Relative weight of Community complaints criteria	Multi-Criteria decision making	E-waste	1	[165]
		Likert scale of Community complaints criteria	Statistical analysis	E-waste	1	[158]
Social inclusion	Quantitative	Number of e-waste workers and relatives provided with social and psychological assistance	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]
		Number of new e-waste workers that come from specific groups	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]
Waste recycled	Quantitative	Quantity of WEEE recycled	Game theory	E-waste	1	[162]
Community service	Quantitative	Hours dedicated for community service	Multi-Criteria and Optimization	E-waste	1	[116]
Products donated to NGOs	Quantitative	Number of products donated to NGOs.	Multi-Criteria and Optimization	E-waste	1	[116]
Risk of transport and installation of facilities	Quantitative	Number of people around the route and facility	Optimization	Hazardous waste	1	[148]
Effect of production on self-sufficiency	Quantitative	Coefficient of production effect on self-sufficiency	Optimization	Light bulbs	1	[150]
Social support	Quantitative	Level of social support of facility	Optimization	Magnets	1	[151]
Social cost based on disposal	Quantitative	Cost per unit quantity disposed to environment	Optimization	Medical waste	1	[121]
Reduction of vehicle accident rate	Quantitative	vehicle accident rate proposed the function	Optimization	Perishable products	1	[122]
Vehicle noise emission	Quantitative	Amount of vehicle noise emission function	Optimization	Perishable products	1	[122]
Respect for the local rules and policies	Qualitative	Relative weight of Respect for the local rules and policies criteria	Multi-Criteria and Optimization	Plastic	1	[74]
Ecological risk and safety risk	Qualitative	Relative weight of Ecological risk and safety risk criteria	Multi-Criteria decision making	End of life vehicles	1	[134]
Communities Influence	Qualitative	Relative weight of Communities Influence criteria	Multi-Criteria decision making	E-waste	1	[118]
Disturbance in Public Places	Qualitative	Fuzzy weights of Disturbance in Public Places criteria	Multi-Criteria decision making	Municipal solid waste	1	[137]
Community capital	No indicator	Without indicator	Qualitative analysis	General	1	[168]
Demanding customer/Stakeholders Pressure	No indicator	Without indicator	Statistical analysis	General	1	[168]

Appendix II.4. Company-oriented social criteria

Table 34. Company-oriented social criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Green image	Quantitative	Increase in customer goodwill due to greening activities	Case study analysis	General	1	[159]
		Percentage with respect to reuse index and market behavior	System Dynamics	E-waste	1	[125]
		Relation between "Market behavior" and "reuse index"	System Dynamics	E-waste	1	[124]
	Qualitative	Relative weight of Green Image criteria	Multi-Criteria decision making	Light bulbs	1	[136]
	No indicator	Without indicator	Multi-Criteria and Optimization	Bicycles	1	[131]
customer satisfaction	Quantitative	Percentage of customers who are satisfied with the final products	Hybrid BSC-DEA (balanced scorecard - data envelopment analysis)	Plastic	1	[77]
		Percentage of demand satisfied	Optimization	General	1	[120]
	Qualitative	Relative weight of Brand image & customer satisfaction criteria	Multi-Criteria decision making	End of life vehicles	1	[134]
				General	1	[166]
No indicator	Without indicator	Interpretive Structural Modeling (ISM)	Paper	1	[115]	
Corporate Image	Qualitative	Relative weight of Brand image & Customer satisfaction criteria	Multi-Criteria decision making	End of life vehicles	1	[134]
		Relative weight of Social performance criteria	Multi-Criteria decision making	End of life vehicles	1	[133]
		Relative weight of Corporate Image criteria	Multi-Criteria decision making	E-waste	1	[118]
		Likert Scale of Corporate Image criteria	Statistical analysis	General	1	[170]
Income generation	Quantitative	Monetary incomes	Composition of Probabilistic Preferences (CPP) and LCA	E-waste	1	[160]
			Discrete event simulation (DES)	Municipal solid waste	1	[66]
			Financial analysis	E-waste	1	[75]
Stake holder's participation	Qualitative	Relative weight of Stake holder's participation criteria	Multi-Criteria decision making	E-waste	1	[165]
		Likert scale of Stake holder's participation criteria	Statistical analysis	E-waste	1	[158]

Appendix II.5. Other social criteria

Table 35. Other social criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Percent recycling	Quantitative	Increase in recycled material compared to material disposal	Case study analysis	General	1	[159]
Product green efficiency	Quantitative	Increase of green design features in a product, number of parts, etc.	Case study analysis	General	1	[159]
Amount of expired products	Quantitative	Age and price policy in the model	Optimization	Perishable products	1	[122]
Effective communication (EC)	Qualitative	Relative weight of Effective communication criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Service improvement	Qualitative	Relative weight of Service improvement criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Overall working relations	Qualitative	Relative weight of Overall working relations criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Public acceptability	Qualitative	Relative weight Social performance criteria	Multi-Criteria decision making	End of life vehicles	1	[133]
Market demand	Qualitative	Relative weight of Market demand criteria	Multi-Criteria decision making	E-waste	1	[135]
Contractual stakeholders influence	Qualitative	Relative weight of Contractual stakeholder's influence criteria	Multi-Criteria decision making	Light bulbs	1	[136]
Reputation	Qualitative	Relative weight of Reputation criteria	Multi-Criteria decision making	Light bulbs	1	[136]
Road safety	Qualitative	Fuzzy weights of Road safety criteria	Multi-Criteria decision making	Municipal solid waste	1	[137]
Health of road	Qualitative	Fuzzy weights of Health of road criteria	Multi-Criteria decision making	Municipal solid waste	1	[137]
Distribution Services	Qualitative	Fuzzy weights of Distribution Services criteria	Multi-Criteria decision making	Municipal solid waste	1	[137]
Access to markets	Qualitative	Fuzzy weights of Access to markets criteria	Multi-Criteria decision making	Municipal solid waste	1	[137]
Market edge	No indicator	Without indicator	Interpretive Structural Modeling (ISM)	Paper	1	[115]
Customer redundancy	No indicator	Without indicator	Interpretive Structural Modeling (ISM)	Paper	1	[115]
Productive capital	No indicator	Without indicator	Qualitative analysis	General	1	[168]

Appendix II.6. Incentive/punishment-oriented policies

Table 36. Incentive/punishment-oriented policies

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Subsidy	Quantitative	The subsidy of collect EOL products per unit collected	Action research	E-waste	1	[172]
			Game theory	Cooking oil	1	[173]
				General	2	[154], [155]
				Photovoltaic technologies	1	[214]
			Multi-Criteria and Optimization	E-waste	1	[156]
			Optimization	E-waste	1	[83]
				General	2	[120], [176]
			Quality-based price competition model	E-waste	1	[180]
			System Dynamics and grey model theory	Construction and demolition wastes	1	[217]
			Theoretical model	E-waste	1	[218]
Variational inequality	General	1	[128]			
Degree of subsidy for remanufacturing technology	Game theory	General	2	[114], [174]		
Subsidy to investment	Game theory	General	1	[113]		
Subsidy to the consumer (price)	Game theory	General	1	[113]		
Percentage of subsidy earned from the government for training employees	Multi-Criteria and Optimization	E-waste	1	[116]		
Taxes	Quantitative	Carbon tax (Tax per carbon emission)	Optimization	General	1	[175]
				Tire	1	[179]
			Variational inequality	General	1	[128]
		Recovery taxes (monetary unit/per pound)	Game theory	E-waste	1	[112]
		Per unit tax credit from donation of returns	Multi-Criteria and Optimization	E-waste	1	[116]
		Landfill tax	Optimization	Metal	1	[178]
		Tax in case the firm does not comply with the Legislative Collection Percentage	System Dynamics	E-waste	1	[126]
		Tax for scavengers' uncontrollable disposal	System Dynamics	E-waste	1	[126]
		Tax if the firm does not comply with the Legislative Recycling Percentage	System Dynamics	E-waste	1	[126]
		Tax to new product (recycling fee per product)	Theoretical model	E-waste	1	[218]
Penalties	Quantitative	Emission penalties (Unit emission social responsibility cost for the government)	Game theory	E-waste	1	[112]
		Penalty cost by use of paper or plastic in packaging	Optimization	General	1	[51]
		Penalty for non-recyclable product disposed as landfill	Optimization	Medical waste	1	[121]
		Cost per item due to regulatory non-compliance	System Dynamics	E-waste	1	[125]
		Penalty for illegally dumped waste	System Dynamics and grey model theory	Construction and demolition wastes	1	[217]
Reward and punishment policy to recycler	Quantitative	Rewards and punishment to recovery rate limit	Game theory	General	1	[174]
Credit lines to investment	Quantitative	Formalization ratio due to environmental policies	System Dynamics	E-waste	1	[127]
Financial incentives	Quantitative	Formalization ratio due to environmental policies	System Dynamics	E-waste	1	[127]
Waste disposal charging fee	Quantitative	Waste disposal charging fee per product	System Dynamics and grey model theory	Construction and demolition wastes	1	[217]
Responsibilities and penalties (sanctions) of citizens and companies	No indicator	Without indicator	Surveys Analysis	General	1	[181]

Appendix II.7. Emission policies

Table 37. Emission policies

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Emission quota	Quantitative	Quantity of emissions	Optimization	General	2	[175], [176]
				Medical waste	1	[121]
			Plastic	1	[106]	
			Variational inequality	General	1	[128]
Emission cap	Quantitative	Maximum amount of a particular pollutant which can be produced	Optimization	General	3	[175]–[177]
				Medical waste	1	[121]
				Plastic	1	[106]
Emission standards	No indicator	Without indicator	Surveys Analysis	General	1	[181]

Appendix II.8. Legal criteria

Table 38. Legal criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference		
Legislation	Quant	Minimum Legislative recycling percentage (product accepted for recycling vs collected)	System Dynamics	E-waste	3	[125]		
						[126]		
						[124]		
		Minimum Legislative Collection Percentage (Fraction of Collected Products vs Used Products)	System Dynamics	E-waste	3	[125]		
						[126]		
						[124]		
	Minimum Legislative limit of recyclability (Recyclable percentage of the product)	System Dynamics	E-waste	2	[125]			
					[124]			
	Legal Minimum amount of waste to be submitted	Game theory	Cooking oil	1	[173]			
					Legal collection goal (percentage at which product should be collected)	Optimization	E-waste	1
	No indicator	Without indicator	Minimum Legislative Limit of Recycled Content (use of recycled material sin production)	System Dynamics	E-waste	1	[125]	
							Relative weight of respect for the local rules and policies criteria	Multi-Criteria and Optimization
				Relative weight of Regulatory Satisfaction criteria	Multi-Criteria decision making	E-waste	1	[118]
				Likert scale of Government rules and Regulation criteria	Statistical analysis	E-waste	1	[158]
Discounted cash flow					Municipal solid waste	1	[111]	
Interpretive Structural Modeling (ISM)					Paper	1	[115]	
PESTLE analysis					Plastic	1	[50]	
Qualitative analysis					E-waste	1	[219]	
Adherence to legal norms	No indicator	Without indicator	Multi-Criteria and Optimization	E-waste	1	[116]		
						Photovoltaic technologies	1	[123]
				Tire	1	[157]		

Appendix II.9. Active government policies

Table 39. Active government policies

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Imposition of the RL network	No indicator	Without indicator	Cost analysis	E-waste	1	[78]
			Optimization	Municipal solid waste	1	[68]
Government's stockpile	Quantitative	Stockpile amount of product	Optimization	Rare metals	1	[215]
Incorporation of Governmental collection center	No indicator	Without indicator	Game theory	General	1	[55]
Imposition of reduction rate and selling price of product	No indicator	Without indicator	Game theory	General	1	[55]
Flow Conditions of waste policy	No indicator	Without indicator	Optimization	Municipal solid waste	1	[68]

Appendix II.10. Other policies

Table 40. Other policies

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Vehicle noise emission	Quantitative	Maximum allowed vehicle noise emission	Optimization	Perishable products	1	[122]
Imposition of quality threshold	Quantitative	Minimum quality threshold of reusing (Number between 0 and 1)	Quality-based price competition model	E-waste	1	[180]
Qualification of waste pickers through capacitation actions	Quantitative	Formalization ratio due to environmental policies	System Dynamics	E-waste	1	[127]
Training and technical assistance	Quantitative	Formalization ratio due to environmental policies	System Dynamics	E-waste	1	[127]
Tactics	Quantitative	Mathematical relationship between Desired Collection and Sustain Product	System Dynamics	E-waste	1	[125]
Compliance with International Labor Organization (ILO) code	Qualitative	Relative weight of Compliance with International Labor Organization criteria	Multi-Criteria and Optimization	E-waste	1	[117]
Technology specifications	No indicator	Without indicator	Surveys Analysis	General	1	[181]
product bans and use limitations	No indicator	Without indicator	Surveys Analysis	General	1	[181]
Requirements for the hazardous waste management	No indicator	Without indicator	Surveys Analysis	General	1	[181]
Solid waste and packing regulation	No indicator	Without indicator	Surveys Analysis	General	1	[181]
Imposition of mandatory collection	No indicator	Without indicator	System Dynamics	E-waste	1	[181]

Appendix II.11. Process-oriented technological criteria

Table 41. Process-oriented technological criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Capacity of facilities	Quantitative	Amount of product	Game theory	Cooking oil	1	[173]
			Grey prediction model and Optimization	Medical waste	1	[183]
			Multi-Criteria and Optimization	Bicycles	1	[131]
				E-waste	2	[116], [117]
			Optimization	Apparel	1	[185]
				Automotive industry	1	[186]
				Building waste	1	[188]
				Carbon fiber reinforced polymers (CFRP)	1	[69]
				End of life vehicles	1	[190]
				E-waste	7	[58], [83], [119], [139], [142], [191], [193]
				General	18	[51], [120], [143]–[146], [175], [176], [195]–[200], [202]–[205]
				Glass	1	[147]
				Hazardous waste	1	[148]
				Household waste	1	[206]
				Kitchenware	1	[149]
				Light bulbs	1	[150]
				Magnets	1	[151]
				Medical waste	2	[121], [152]
				Metal	1	[178]
				Municipal solid waste	3	[68], [153], [207]
				Photovoltaic technologies	1	[208]
				Plastic bottles	2	[52], [53]
				Plastic pallets	1	[60]
				Post-consumer packages	1	[209]
			Solar energy industry	1	[210]	
			Tire	2	[46] [179]	
			Optimization and LCA	Plastic	1	[67]
			System Dynamics	End of life vehicles	1	[213]
	E-waste	2		[126], [127]		
Gold from cellphones	1	[11]				
Variational inequality	General	1	[128]			
No indicator	Without indicator	PESTLE analysis	Plastic	1	[50]	
		Qualitative analysis	Photovoltaic technologies	1	[123]	

Table 41. Process-oriented technological criteria (continuation)

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference		
Technology selection	Quantitative	Capacity level using technology type	Optimization	Batteries	1	[187]		
				Construction and demolition wastes	1	[138]		
				E-waste	2	[139] 34]		
				General	1	[144]		
				Hazardous waste	1	[148]		
				Solar energy industry	1	[210]		
	No indicator	Without indicator	Optimization	Light bulbs	1	[150]		
	Recycling rate	Quantitative	Recycling rate of product	Optimization	Discounted cash flow	Municipal solid waste	1	[111]
Optimization					Medical waste	1	[152]	
Optimization					Tire	2	[46], [179]	
Optimization					Batteries	1	[187]	
Statistical analysis				System Dynamics	Variational inequality	E-waste	1	[58]
						General	2	[146], [203]
						Medical waste	1	[121]
						Plastic bottles	1	[53]
Steel	1	[212]						
E-waste	2	[126], [127]						
Gold from cellphones	1	[11]						
General	1	[128]						
Processing time	Quantitative	Processing time per unit of product	Optimization	E-waste	1	[83]		
				Optimization	Food industry	1	[194]	
				Optimization	Photovoltaic technologies	1	[208]	
	No indicator		Without indicator	Interpretive Structural Modeling (ISM)	System Dynamics	E-waste	1	[127]
					Interpretive Structural Modeling (ISM)	Paper	1	[115]
Recovery options	No indicator	Without indicator	Discrete event simulation (DES)	Municipal solid waste	1	[66]		
				E-waste	1	[135]		
			Multi-Criteria decision making	Municipal solid waste	1	[137]		
				E-waste	1	[192]		
			Optimization	Plastic	1	[10]		
Capacity extension	Quantitative	Quantity of expanding capacity level	Optimization	Construction and demolition wastes	1	[138]		
				E-waste	1	[191]		
				Light bulbs	1	[150]		
				Solar energy industry	1	[210]		
				Quality of the returned products	Quantitative	Number between 0 and 1	Optimization	General
Quality-based price competition model	E-waste	1	[180]					
Quality of recycled product	Quantitative	Quality factor of recycled product	Game theory	General	1	[174]		
		Number between 0 and 1	Quality-based price competition model	E-waste	1	[180]		
	Qualitative	Relative weight of Quality of product criteria	Multi-Criteria decision making	Light bulbs	1	[136]		
Technical feasibility of recycling	Qualitative	Relative weight of Technical/ operational feasibility criteria	Multi-Criteria decision making	E-waste	1	[136]		
				Qualitative analysis	Photovoltaic technologies	1	[123]	
	No indicator	Without indicator	Surveys Analysis	General	1	[181]		
Capacity of equipment	Quantitative	Amount of product	Optimization	Batteries	1	[187]		
				Photovoltaic technologies	1	[208]		

Table 41. Process-oriented technological criteria (continuation)

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Capacity per product	Quantitative	Amount of product	Optimization	General	1	[177]
				Post-consumer packages	1	[209]
Conversion rate	Quantitative	Conversion rate of repaired or recycled products	Optimization	General	1	[199]
		Conversion coefficient from chips to a bottle	Optimization	Plastic bottles	1	[53]
Capacity using recycling technique	Quantitative	Amount of product	Optimization	Carbon fiber reinforced polymers (CFRP)	1	[69]
Compatibility between wastes and applied technology in the facility	Quantitative	Binary parameter (yes, no)	Optimization	Hazardous waste	1	[148]
Difficulty coefficient of recycling worn-out products	No indicator	Without indicator	Game theory	General	1	[129]
Necessary technology of the recovery centers	No indicator	Without indicator	PESTLE analysis	Plastic	1	[50]

Appendix II.12. Non process-oriented technological criteria

Table 42. Non process-oriented technological criteria

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Capacity of vehicles	Quantitative	Amount of product	Game theory	General	1	[114]
			Multi-Criteria and Optimization	E-waste	1	[116]
			Optimization	Automotive industry	1	[186]
				End of life vehicles	1	[189]
				E-waste	1	[58]
				Food industry	1	[194]
				General	5	[144], [145], [198], [202], [205]
				Hazardous waste	1	[148]
				Household waste	1	[206]
				Kitchenware	1	[149]
				Light bulbs	1	[150]
				Municipal solid waste	1	[207]
			Perishable products	1	[122]	
Vegetable oil	1	[211]				
Optimization and LCA	Plastic	1	[67]			
System Dynamics	E-waste	1	[140]			
Variational inequality	General	1	[128]			
Green technology innovation	Quantitative	Level of green innovation	Game theory	General	2	[113], [130]
	No indicator	Relative weigh of Green technology innovation criteria	Multi-Criteria decision making	End of life vehicles	2	[133], [134]
Use of new technology	No indicator	Without indicator	Action research	E-waste	1	[172]
			Game theory	E-waste	1	[182]
			Optimization	Household waste	1	[206]
Design for environment products	Quantitative	Design for environment products ratio (firms' reaction)	System Dynamics	E-waste	1	[124]
		Minimum Limit of Recyclability (percentage)	System Dynamics	E-waste	1	[125]
Technology transfer	Qualitative	Relative weigh of Technology transfer criteria	Multi-Criteria decision making	End of life vehicles	2	[133], [134]
Capacity utilization	Qualitative	Relative weight of Capacity utilization criteria	Multi-Criteria decision making	E-waste	1	[184]
	No indicator	Without indicator	Interpretive Structural Modeling (ISM)	Paper	1	[115]
Effort to improve the level of technology	Quantitative	Effort cost to improve the level of technology	Game theory	General	1	[174]
Green rate	Quantitative	Rate of energy saved and resources	Game theory	General	1	[114]
Technological expertise	Qualitative	Relative weight of Technological expertise criteria	Multi-Criteria and Optimization	E-waste	1	[117]
Research and development for new products	Qualitative	Relative weigh of Research and development for new products criteria	Multi-Criteria decision making	End of life vehicles	1	[134]
Expert decision and skill manpower	Qualitative	Relative weigh of Expert decision and skill manpower criteria	Multi-Criteria decision making	End of life vehicles	1	[134]
Warehouse management	Qualitative	Relative weight of Warehouse management criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Transportation management	Qualitative	Relative weight of Transportation management criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Inventory management	Qualitative	Relative weight of Inventory management criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
JIT philosophy	Qualitative	Relative weight of JIT philosophy criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Information technology (IT)	Qualitative	Relative weight of Information technology (IT) criteria	Multi-Criteria decision making	End of life vehicles	1	[132]
Demand forecasting	Qualitative	Relative weight of Demand forecasting criteria	Multi-Criteria decision making	End of life vehicles	1	[132]

Table 42. Non process-oriented technological criteria (continuation)

Criteria	Type of indicator	Indicator	Method	Product	Number of articles	Reference
Capability of disassembly infrastructure	Qualitative	Relative weight of Capability of disassembly infrastructure criteria	Multi-Criteria decision making	E-waste	1	[184]
Resource Capacity	Qualitative	Relative weight of Relative weight of Resource Capacity criteria	Multi-Criteria decision making	E-waste	1	[118]
Communication Systems	Qualitative	Relative weight of Communication Systems criteria	Multi-Criteria decision making	E-waste	1	[118]
Specialized infrastructures	Qualitative	Relative weight of Specialized infrastructures criteria	Multi-Criteria decision making	Light bulbs	1	[136]
Investment parameter to sustainably improve recovery technology at the recycling center	No indicator	Without indicator	Game theory	E-waste	1	[112]
Green innovation level	No indicator	Without indicator	Game theory	General	1	[129]
Clean and upgraded technology	No indicator	Without indicator	Multi-Criteria and Optimization	E-waste	1	[116]
Means of transport for waste	No indicator	Without indicator	PESTLE analysis	Plastic	1	[50]
sells options of discarded product (collect)	No indicator	Without indicator	PESTLE analysis	Plastic	1	[50]

Appendix Chapter IV.

Appendix IV.1. Distance between schools/high schools

Table 43. Distance between schools/high schools (km)

	LF2L	Lycée professionnel Paul Louis Cyffle	Collège/Lycée Charles De Foucauld	Lycée professionnel Claude Daunot	Collège/Lycée Saint Dominique	Lycée général et technologique Jeanne D'Arc	Collège/Lycée Notre Dame Saint Sigisbert	Collège Alfred Mezieres	Lycée professionnel Les Métiers De La Beauté	Collège La Craffe	Lycée général et technologique Henri Poincare	Collège Guynemer	Lycée général et technologique Henri Loritz	Collège/Lycée Saint Leon Ix	Collège Louis Armand	Lycée professionnel Marie Immaculee	Collège Du Sacre Coeur	Collège/Lycée Frederic Chopin	Lycée technique Compagnie De Formation-Pigier	Collège/Lycée général et technologique Georges De La Tour	Lycée professionnel Pierre De Coubertin	Collège Collège Montessori Grand-Est	Lycée professionnel Jean Prouve	Collège Jean Lamour
LF2L	0	2	1	3	2	2	3	3	5	3	2	2	2	4	7	2	5	4	3	17	3	4	3	4
Lycée professionnel Paul Louis Cyffle	2	0	1	1	1	1	2	2	2	2	0.963	0.24	0.994	2	4	0.72	2	2	2	4	1	2	2	3
Collège/Lycée Charles De Foucauld	2	0.98	0	2	0.727	2	2	3	3	3	2	1	0.567	3	4	1	4	3	2	5	2	3	2	4
Lycée professionnel Claude Daunot	6	1	2	0	3	4	3	3	2	3	2	2	2	3	0.585	2	2	3	4	0.735	2	2	3	3
Collège/Lycée Saint Dominique	2	0.823	0.166	2	0	2	2	4	2	2	1	1	0.733	2	4	1	3	3	2	5	2	2	3	4
Lycée général et technologique Jeanne D'Arc	2	1	0.672	2	0.506	0	2	3	3	3	2	1	1	3	5	2	3	3	2	5	2	3	3	4
Collège/Lycée Notre Dame Saint Sigisbert	3	1	2	2	1	1	0	2	2	1	0.471	0.966	2	1	5	2	2	2	1	4	2	2	3	3
Collège Alfred Mezieres	4	2	3	4	3	3	0.912	0	2	1	1	2	3	2	6	3	3	3	0.653	3	3	2	5	0.97
Lycée professionnel Les Métiers De La Beauté	4	2	3	2	3	2	3	2	0	2	1	1	2	0.62	3	2	1	0.785	2	3	2	0.287	4	3
Collège La Craffe	3	2	3	4	3	2	0.532	1	2	0	1	1	3	2	5	2	3	3	0.273	3	3	2	4	2
Lycée général et technologique Henri Poincare	2	0.736	1	2	0.967	0.84	1	2	1	1	0	0.496	2	1	5	1	2	2	0.947	4	2	2	3	2
Collège Guynemer	2	0.24	1	1	2	2	2	2	1	2	0.747	0	1	1	4	0.758	2	2	1	4	1	2	2	3
Lycée général et technologique Henri Loritz	1	1	0.485	2	0.734	2	2	3	3	3	2	1	0	3	7	2	3	3	2	5	2	3	3	4
Collège/Lycée Saint Leon Ix	3	0.923	2	3	2	2	2	2	0.86	2	0.654	0.683	2	0	4	1	1	2	2	3	3	1	3	2
Collège Louis Armand	7	3	4	2	4	5	5	5	3	5	4	3	4	3	0	3	2	2	5	4	3	2	4	9
Lycée professionnel Marie Immaculee	3	0.907	2	0.722	2	3	3	3	2	3	2	0.945	2	2	3	0	2	2	3	4	0.534	2	2	3
Collège Du Sacre Coeur	4	2	3	3	3	2	3	2	0.92	3	2	2	3	0.894	3	2	0	1	2	2	2	0.561	4	3
Collège/Lycée Frederic Chopin	3	2	2	2	3	4	3	3	2	3	2	2	2	1	2	2	1	0	3	4	2	0.883	4	4
Lycée technique Compagnie De Formation-Pigier	3	1	2	3	2	2	0.259	1	2	0.58	0.73	1	2	2	5	2	2	2	0	3	3	2	3	2
Collège/Lycée général et technologique Georges De La Tour	6	4	5	5	6	5	4	3	3	4	4	4	5	3	4	5	3	3	4	0	4	3	6	4
Lycée professionnel Pierre De Coubertin	3	1	2	0.717	2	3	3	3	2	3	2	1	2	2	3	0.443	2	4	3	4	0	2	2	3
Collège Collège Montessori Grand-Est	3	1	2	2	3	2	2	2	1	2	1	1	2	2	3	2	2	1	2	3	1	0	3	2
Lycée professionnel Jean Prouve	3	2	3	2	3	3	4	5	4	4	3	2	2	4	4	2	4	3	4	6	2	3	0	5
Collège Jean Lamour	5	3	4	4	3	4	2	0.961	2	2	2	3	4	2	9	4	3	3	2	3	3	3	5	0

Appendix IV.2. Speed between schools/high schools

Table 44. Speed between schools/high schools (km/h)

	LF2L	Lycée professionnel Paul Louis Cyffle	Collège/Lycée Charles De Foucauld	Lycée professionnel Claude Daunot	Collège/Lycée Saint Dominique	Lycée général et technologique Jeanne D'Arc	Collège/Lycée Notre Dame Saint Sigisbert	Collège Alfred Mezieres	Lycée professionnel Les Métiers De La Beauté	Collège La Craffe	Lycée général et technologique Henri Poincare	Collège Guynemer	Lycée général et technologique Henri Loritz	Collège/Lycée Saint Leon IX	Collège Louis Armand	Lycée professionnel Marie Immaculee	Collège Du Sacre Coeur	Collège/Lycée Frederic Chopin	Lycée technique Compagnie De Formation-Pigier	Collège/Lycée général et technologique Georges De La Tour	Lycée professionnel Pierre De Coubertin	Collège Collège Montessori Grand-Est	Lycée professionnel Jean Prouve	Collège Jean Lamour
LF2L	0	15	12	20	20	24	20	20	23	26	11	13	24	18	28	17	21	20	23	68	20	18	20	22
Lycée professionnel Paul Louis Cyffle	17	0	15	15	12	12	20	15	20	20	14	14	20	20	24	22	17	24	24	22	15	24	24	20
Collège/Lycée Charles De Foucauld	20	15	0	17	15	24	13	20	18	23	17	10	17	18	17	12	20	20	15	20	20	18	15	22
Lycée professionnel Claude Daunot	36	12	17	0	23	24	18	18	17	16	17	24	20	15	23	35	15	30	18	20	15	17	24	18
Collège/Lycée Saint Dominique	17	12	10	15	0	20	15	24	12	13	10	12	22	12	16	10	16	18	15	21	17	13	23	20
Lycée général et technologique Jeanne D'Arc	20	12	20	15	15	0	13	20	16	26	17	10	12	16	19	20	15	18	13	20	15	18	20	22
Collège/Lycée Notre Dame Saint Sigisbert	18	15	20	17	12	12	0	24	24	15	28	19	20	12	25	24	20	17	20	27	17	20	23	26
Collège Alfred Mezieres	24	17	20	24	23	26	27	0	24	20	15	20	20	20	30	18	26	23	20	30	20	17	23	29
Lycée professionnel Les Métiers De La Beauté	22	20	23	20	20	13	26	15	0	13	12	12	17	19	26	20	15	24	15	26	24	17	30	26
Collège La Craffe	18	20	23	24	26	20	32	20	24	0	20	12	23	20	25	17	26	23	16	23	20	20	24	60
Lycée général et technologique Henri Poincare	15	22	15	20	15	17	20	24	12	15	0	30	24	12	25	15	17	17	19	27	24	20	26	17
Collège Guynemer	17	14	15	15	24	20	24	17	12	17	15	0	20	10	24	23	17	24	10	24	15	24	24	23
Lycée général et technologique Henri Loritz	12	12	29	13	15	24	13	20	16	26	17	10	0	16	28	17	15	15	12	30	13	18	20	22
Collège/Lycée Saint Leon IX	18	14	17	26	17	17	24	20	17	17	13	14	20	0	24	10	15	24	20	26	30	15	23	24
Collège Louis Armand	30	20	22	20	20	21	23	23	23	20	22	20	24	23	0	26	24	40	21	34	23	20	27	45
Lycée professionnel Marie Immaculee	23	18	24	43	20	23	20	20	20	20	20	19	30	17	20	0	17	30	23	22	32	24	40	20
Collège Du Sacre Coeur	20	17	20	26	18	12	23	17	18	18	20	20	23	18	26	17	0	20	13	20	20	17	27	26
Collège/Lycée Frederic Chopin	18	24	17	24	23	24	20	18	30	16	17	24	20	20	24	24	15	0	18	27	30	26	34	27
Lycée technique Compagnie De Formation-Pigier	18	12	17	20	20	24	16	20	30	17	22	15	17	30	27	20	20	17	0	23	26	24	20	60
Collège/Lycée général et technologique Georges De La Tour	21	20	21	25	24	23	27	26	36	24	24	22	23	23	48	25	30	23	30	0	22	26	26	34
Lycée professionnel Pierre De Coubertin	18	12	17	22	15	18	18	18	17	16	15	12	20	15	23	27	15	60	18	20	0	20	24	18
Collège Collège Montessori Grand-Est	18	12	17	24	23	15	17	17	15	15	12	12	20	24	23	24	24	15	17	20	15	0	26	17
Lycée professionnel Jean Prouve	23	17	23	24	20	20	20	23	24	22	18	15	20	22	24	30	22	20	20	24	20	18	0	23
Collège Jean Lamour	23	18	20	24	18	27	24	29	20	24	20	23	22	20	42	24	26	23	30	26	20	26	23	0

Appendix Chapter V.

Appendix V.1. Recycled filament demand assumption

The demand for recycled filament and the demand for virgin filament have been modeled as follows:

$$\text{Demand for recycled filament} = N3DP * FC * [\alpha * (Pr - Pv) + \beta * Prf] \quad (1)$$

$$\text{Demand for virgin filament} = N3DP * FC * [1 - (\alpha * (Pr - Pv) + \beta * Prf)] \quad (2)$$

Where:

$N3DP$: Numbers of 3D printers

FC : Filament consumption per printer

α : Sensitivity factor for the price of recycled filament vs. virgin filament

Pr : Price of recycled filament

Pv : Price of virgin filament

β : Sensitivity factor for the use of recycled filament vs virgin filament

Prf : Performance of recycled filament vs virgin

As can be seen from the equations, the demand for each type of filament is established by a function that determines the proportion of the demand for filament (in general) that prefers virgin or recycled filament. The proportion of the filament demand that prefers each type of filament is defined by the difference between the prices of each filament and the performance of the recycled vs. virgin filament. By performance, it can be understood the quality of the recycled vs. virgin filament, the print quality obtained with the recycled vs. virgin filament, or another type of reference determined by the users (which determines their preference). As an example, [Figure 125](#) shows the behavior of the recycled filament demand with respect to a demand of 10 kg of filament, a sensitivity of -0.05 with respect to prices and a sensitivity of 0.5 with respect to the use of recycled filament. These same sensitivity values have been considered in the model.

$$\text{Demand for recycled filament} = 10 * [-0.05 * (Pr - Pv) + 0.5 * Prf] \quad (3)$$

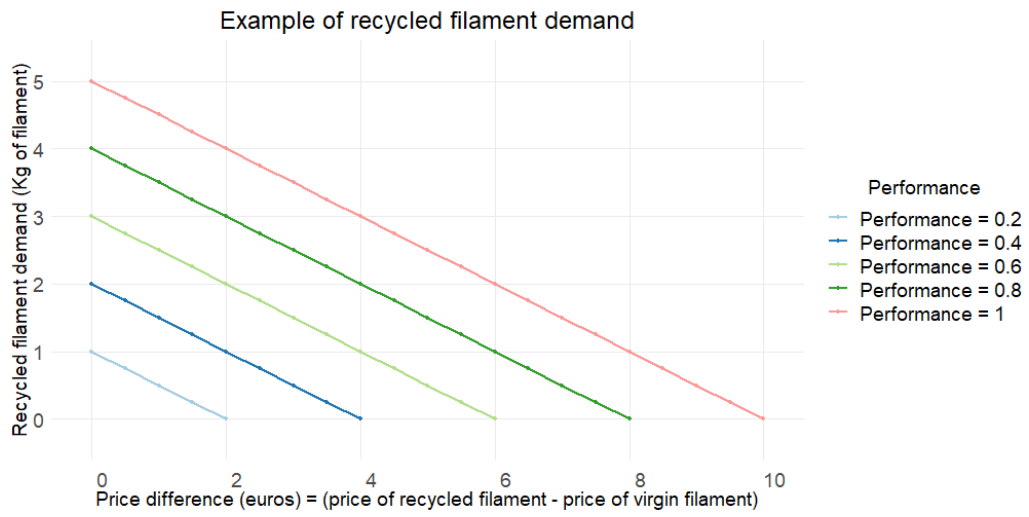


Figure 125. Example of recycled filament demand considering a filament demand of 10 Kg

Appendix V.1. Collection cost calculation

The cost of collection has been calculated considering the optimal route obtained in chapter IV (application of the optimization model developed to the case study). The distance of the optimal route is 26,515 km in a car with an average speed of 21 km/h. Then, the collection cost is defined as:

$$CC = \frac{\text{Hours per route} * \text{Labour cost of transport} + \text{Distance of route} * \text{cost of vehicle use}}{\text{Amount of plastic waste collected} * \text{Recyclability rate of reference} * \text{Conversion rate}}$$

Where:

$$\text{Hours per route} = \frac{\text{Distance per route}}{\text{Average speed}}$$

Since the cost of collection must be a function of the amount of recycled filament obtained (potentially), the amount of plastic waste collected is multiplied by a recyclability rate of reference and by the conversion factor of plastic waste to recycled filament. Recyclability rate of reference is considered as the lowest recyclability between 3D plastic waste from recycled plastic and 3D plastic waste from virgin plastic.

Finally, in order to make a collection economically and environmentally more efficient, it is imposed that a route will be made only if the amount to be collected is greater than a previously defined amount (if there is space available to store the plastic waste). In addition, to facilitate the calculation, it is assumed that in each route the previously defined amount will be collected. If the amount of plastic waste to be collected is not sufficient to justify a collection route, it is accumulated with the following periods. For example, given a quantity to be collected of 12.2 Kg and a previously defined amount of 6 Kg to made a route, the amount collected would be 12 Kg (2 routes) and the 200 gr would be accumulated with the following periods. In conclusion, the collection cost per kilogram of recycled filament is defined in the model as:

$$\text{Collection cost} = \frac{\text{Hours per route} * \text{Labour cost of transport} + \text{Distance of route} * \text{cost of vehicle use}}{\text{Amount defined} * \text{Recyclability rate} * \text{Conversion rate}}$$

Valorisation en circuit court de déchets thermoplastiques pour la conception par impression 3D de structures composites.

La gestion des déchets plastiques est un problème majeur qui doit encore être résolu dans la perspective d'un développement plus durable des activités humaines. Parmi les solutions envisageables, le recyclage, est un moyen intéressant de revaloriser ses matières non renouvelables. Après des décennies de recyclage centralisé on observe aujourd'hui un intérêt grandissant pour les approches basées sur le recyclage distribué. Profitant de la démocratisation des technologies d'impression 3D open-source (OS) nous proposons de revaloriser localement les plastiques utilisables par ces technologies. Ce recyclage distribué peut être considéré comme une sorte de "réseau intelligent", composé de petites unités de recyclage coordonnées, qui fournissent des filaments de plastique recyclé à la communauté de l'impression 3D. La faisabilité technique de cette approche de recyclage du plastique a été prouvée dans la littérature. Cependant, sa faisabilité du point de vue de la chaîne d'approvisionnement et de la logistique doit encore être démontrée. Afin d'aborder cette question, cette thèse de recherche cherche à apporter des réponses à la question de recherche suivante : Dans quelles conditions est-il possible de déployer un réseau durable de recyclage local et distribué des plastiques en utilisant des technologies d'impression 3D open-source ? En tenant compte de ce qui précède, ce travail de recherche vise à proposer un cadre pour l'analyse et l'évaluation, du point de vue de la durabilité, de l'approche de recyclage distribué du plastique pour l'impression 3D. Le cadre d'évaluation proposé combine l'optimisation et la dynamique des systèmes dans l'évaluation de la durabilité de l'approche de recyclage. L'application du cadre d'évaluation à une étude de cas spécifique d'une université cherchant à mettre en œuvre un démonstrateur de recyclage distribué afin de récupérer les déchets d'impression 3D des collèges et lycées du nord-est de la France, a illustré la faisabilité du point de vue de la durabilité.

Mots-clés : Chaîne d'approvisionnement, Recyclage des plastiques, Impression 3D, Économie circulaire, Recyclage distribué, Optimisation, Dynamique des systèmes, Durabilité

Short circuit valorization of thermoplastic waste for the conception by 3D printing of composite structures.

The management of plastic waste is a major problem that has yet to be resolved with a view to a more sustainable development of human activities. Among the possible solutions, recycling is an interesting way to recycle non-renewable materials. After decades of centralized recycling, there is now a growing interest in approaches based on distributed recycling. Taking advantage of the democratization of open-source 3D printing technologies (OS), we propose to revalorize locally the plastics that can be used by these technologies. This distributed recycling can be considered as a kind of "intelligent network", composed of small coordinated recycling units, which provide recycled plastic filaments to the 3D printing community. The technical feasibility of this plastic recycling approach has been proven in the literature. However, its feasibility from a supply chain and logistics perspective has yet to be demonstrated. In order to address this issue, this research thesis seeks to provide answers to the following research question: Under what conditions is it possible to deploy a sustainable network of local and distributed plastics recycling using open-source 3D printing technologies? Taking into account the above, this research work aims to propose a framework for the analysis and evaluation, from a sustainability perspective, of the distributed plastic recycling approach for 3D printing. The proposed evaluation framework combines optimization and system dynamics in the evaluation of the sustainability of the recycling approach. The application of the evaluation framework to a specific case study of a university seeking to implement a distributed recycling demonstrator to recover 3D printing waste from middle and high schools in northeastern France illustrated the feasibility from a sustainability perspective.

Keywords: Supply chain, Plastic recycling, 3D printing, Circular economy, Distributed recycling, Optimization, System Dynamics, Sustainability