Resources, Conservation & Recycling 154 (2020) 104531

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Closed loop supply chain network for local and distributed plastic recycling for 3D printing: a MILP-based optimization approach

Pavlo Santander*, Fabio A. Cruz Sanchez, Hakim Boudaoud, Mauricio Camargo

Université de Lorraine, Équipe de Recherche sur les Processus Innovatifs, ERPI, F-54000 Nancy, France

A R T I C L E I N F O

Keywords:
Closed loop supply chain
Plastic recycling
3D printing
Circular economy
Mixed integer linear programming
Distributed recycling

A B S T R A C T

Recent research and initiatives increasingly propose a new approach, based on distributed plastic recycling for open-source (OS) 3D printing technologies, as a way to deal with the issue of plastic waste and to support the development of the circular economy (CE). Distributed recycling can be thought of as a sort of "smart grid", composed of small and coordinated recycling units. However, the operational complexity of this distributed approach limits its application. Furthermore, the environmental and economic advantages have yet to be demonstrated. This article therefore explores the economic and environmental feasibility of this distributed plastic recycling approach from a logistics perspective, as a step towards its validation. To achieve this, an optimization mixed integer linear programming (MILP) model was used as an evaluation tool, representing a local closed loop supply chain (CLSC) network. The proposed model is illustrated using a case study of a university seeking to implement a distributed recycling demonstrator in order to recover 3D printing wastes from secondary schools in the northeast of France. Following this step, a sensitivity analysis was carried out considering the market variations (price of virgin plastic filament) and the amount of available plastic waste derived from the schools. The results obtained show positive economic and environmental benefits of carrying out this new method of plastic recycling. This work serves as a basis for continuing to explore the feasibility and replication of the distributed plastic recycling network in other contexts.

1. Introduction

Plastics are present in a wide variety of products in our everyday lives. However, the amount of plastics which are recycled remains very low: only 14% of the plastic produced in Europe was recycled in 2016 (PlasticsEurope, 2017; Ragaert et al., 2017; Singh et al., 2017). In the current industrial paradigm, the plastic recycling process is commonly carried out through centralized networks in order "to take advantage of economies of scale in producing low-value commodities" (Kreiger et al., 2014). However, this approach must face the challenge of collection and expensive transportation of the high volume and low weight of polymers, as well as requiring significant capital and extensive operating investments (Kreiger et al., 2014; Garmulewicz et al., 2018; Despeisse et al., 2017). This situation makes the plastic recycling process neither economically advantageous, nor environmentally friendly (Kreiger et al., 2014; Garmulewicz et al., 2018; Despeisse et al., 2017). In order to address this plastic recycling issue, the European Union has begun to propose various ambitious objectives to develop a circular economy for plastics. For example, by the year 2030, more than half of all plastic waste generated is expected to be recycled (EU Commission, 2018). 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.

Nevertheless, the development of additive manufacturing (3D printing) technology is opening up opportunities by developing an economically-competitive distributed manufacturing sector, supported by commercial and open-source (OS) 3D printers (Wittbrodt et al., 2013; Gwamuri et al., 2014; Kietzmann et al., 2015; Laplume et al., 2016; Mai et al., 2016; Kostakis et al., 2013; Kostakis and Papachristou, 2014; Kreiger and Pearce, 2013). Indeed, 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 impacts (Kreiger and Pearce, 2013; Matt et al., 2015). More precisely from a supply chain perspective, 3D printing has a widespread expectation to promote many structural changes (e.g. inventory reductions (Zanoni et al., 2019; Verboeket and Krikke, 2019), reduce disassembling efforts (Verboeket and Krikke, 2019), on-demand spare parts (Zhang et al., 2019; Verboeket and Krikke, 2019), customization and personalization (Bogers et al., 2016; Zanoni et al., 2019; Verboeket and Krikke, 2019), decentralized

* Corresponding author.
E-mail addresses: pavlo.santander-tapia@univ-lorraine.fr (P. Santander), pavlo.santander@gmail.com (F.A. Cruz Sanchez).

https://doi.org/10.1016/j.resconrec.2019.104531
Received 18 February 2019; Received in revised form 24 September 2019; Accepted 30 September 2019
Available online 03 December 2019
0921-3449/

production close to the consumers (Bogers et al., 2016; Zanoni et al., 2019; Verboeket and Krikke, 2019), reduce the labor input needed for production (Laplume et al., 2016; Verboeket and Krikke, 2019)). Matt et al. (2015) examined the different types of distributed manufacturing models, which range from distributed manufacturing facilities to sending 3D files to manufacturing via 3D printers. In this latter model, the product is manufactured and assembled in distributed networks of printing labs or small factories with high-performance printers and qualified staff for final assembly and finishing. 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 AM technology (González-Henríquez et al., 2019). Therefore, as the AM technology will continues to grow in the years to come, probably the polymer waste will continue to be disposed anywhere.

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 (Kreiger and Pearce, 2013; Wittbrodt et al., 2013; Baechler et al., 2013). This emerging approach to recycling could be carried out in distributed facilities on a local scale (city, town, or neighborhood-wide) using open-source (OS) technologies. For example, a recent study by Zhong and Pearce (2018) demonstrated that the coupling of an OS extruder (recyclebot) and RepRap 3D printer "brings a traditional industrial system into a single small home, business or community center". Furthermore, various studies in the literature show the technical feasibility of this distributed plastic recycling approach (Kreiger et al., 2014; Cruz Sanchez et al., 2015, 2017; Juraschek et al., 2017; Zhao et al., 2018). The notion of open source (OS) makes it possible to create technically superior and far less expensive equipment than proprietary models (Pearce, 2017; Petersen and Pearce, 2017). 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.

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 supply chain 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 (Garmulewicz et al., 2018). Nevertheless, this approach to distributed plastic recycling also presents some technical, social and economic complexities, barriers and challenges, which must be addressed (Garmulewicz et al., 2018; Peeters et al., 2019). From a technical perspective, the great variety of thermoplastics with different properties and their lack of specificity in the categories, are important barriers identified (Peeters et al., 2019). 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 (Garmulewicz et al., 2018). 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 (Peeters et al., 2019). 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 (Garmulewicz et al., 2018). Finally, from an economical perspective, the uncertainty about return on investment is a barrier identified (Peeters et al., 2019). Mastering operating costs and enhancing added value creation for stakeholders of the recycling system is still crucial to justify any recycling process.

There appear to be few antecedents in the literature of a formal design and evaluation of such plastic recycling network integrating small units of extrusion-3D printing, which represents an important area of research due to its potential application given the current environmental issues. Therefore, it could be said that despite its attractiveness, the complexity of this distributed approach limits its application potential. In order to tackle this issue, this paper seeks to provide answers to the following research question: How to support the logistic decision-making process to evaluate the implementation of a distributed closed loop plastic recycling network?

The contribution of this research is twofold: a first formalization, by means of an optimization model, of the distributed plastic recycling network for distributed manufacturing purposes. Formally, the optimization model enables assessment of the conditions required to ensure the economic and environmental effectiveness of the proposed plastic recycling network. Secondly, the proposed model is illustrated using a case study of a university Fablab aiming to implement a demonstrator to recover 3D printing wastes from secondary schools in the northeast of France. Consequently, this paper constitutes a step towards the validation of this approach.

This article is structured as follows. Section 2 presents an overview of previous works in the literature on OS 3D printing technologies, closed loop supply chain networks for plastic recycling and research about distributed recycling networks. Section 3 presents the optimization model developed herein. Section 4 presents the context of the case study, describing how the optimization was applied. Then, Section 5 presents the results and a sensitivity analysis. Section 6 presents the discussion of the results and finally, Section 7 presents conclusions and perspectives.

2. An overview of distributed recycling of plastics

As mentioned in the previous section, the distributed plastic recycling approach presents some complexities and challenges from social, technical and economic (logistical) points of view. Within the scope of the present research, only the recycling process and the operational logistic network design will be addressed.

2.1. From a process perspective: open-source (OS) as a support technology

Fused deposition modeling (FDM) is one of the first technologies developed in additive manufacturing (AM) technology (ASTM & ISO, 2015). FDM uses the extrusion process, wherein a thermoplastic filament is melted and deposited to generate the product. The simplicity of the process in the FDM renders the required equipment relatively inexpensive. In addition to this, the raw materials used are low-cost, non-toxic, and odorless, making it ideal for hobbyists. The materials most used in FDM are ABS (acrylonitrile butadiene styrene), PLA (polylactic acid), and PC (polycarbonate) (Bikas et al., 2016; Gardan, 2016).

The FDM technology patent expired in the mid-2000s, enabling users to develop this technology in an open-source (OS), non-commercial way, thereby reducing the acquisition costs of this technology and making it accessible to all (Cruz Sanchez et al., 2014). An example of this is the RepRap project, which enabled users to acquire a 3D printer with a budget in the range of \$200–\$500, and it is estimated that, between 2008 and 2011, the number of RepRaps increased from four to 4500 (Kreiger et al., 2014).

All of this lends weight to the study and development of distributed manufacturing using this technology and, at the same time, the distributed plastic recycling approach as a supplier of 3D printing filaments from recycled plastics (Baechler et al., 2013).

In the prosumer domain, there have been a plenty attempts to create open-source versions of extruder in order to create plastic filament: Lyman Filament Extruder (Lyman, 2019), the Filabot (McNaney, 2019), Recyclebot (Baechler et al., 2013), RepRap Recycle Add-on (Braanker et al., 2010), Precious plastic (Hakkens, 2019), Plastic Bank.[1] Indeed, various studies in the scientific literature have focused on the mechanical and distributed plastic recycling process in order to demonstrate its technical feasibility. Woern et al. (2018) published a plastic waste extruder capable of making commercial quality 3-D printing filament. This device design takes advantage of the OS hardware approach (free, self-replicated and modular). The design, fabrication and operation are described. The device costs less than $700 in materials and can be made in approximately 24 h. Filament is produced at 0.4 kg/h using 0.24 kWh/kg with a diameter of ± 4.6%. Likewise, Kreiger et al. (2014) demonstrated the environmental feasibility in terms of energy use and greenhouse gas emissions from distributed mechanical recycling of HDPE using the RecycleBot extruder. Similarly, Cruz Sanchez et al. (2015) demonstrated the technical viability for PLA mechanical recycling for OS 3D printers. Furthermore, Cruz Sanchez et al. (2017) proposed a general methodology to evaluate the recyclability of polymers used as feedstock for 3D printing. Based on the closed loop approach and with process orientation, Juraschek et al. (2017) studied closed loop manufacturing in a learning environment, considering plastic recycling and its use in 3D printers. On the other hand, Zhao et al. (2018) studied the material properties of the closed-loop recycling of PLA and demonstrated its environmental benefits. In conclusion, the technical feasibility of distributed recycling from a process perspective using OS technologies has already been presented in the scientific literature. Also, this technical aspect opens up the opportunity to create of specific and small-scale recycling hubs specific to obtain usable feed-stock for 3D printing.

Nevertheless, from a supply chain perspective, the logistic effectiveness of distributed recycling networks for this additive technologies remains to be demonstrated. An overview of the logistic perspective of recycling is presented in next section.

2.2. From a logistic perspective: a closed loop supply chain and distributed recycling network

Recycling is an activity carried out in order "to have more raw materials or raw parts" from used products (Govindan et al., 2015). If we consider the literature on recycling networks, we can see that, on the whole, two types of networks coexist (Govindan et al., 2015): reverse supply chain (RSC) (or reverse logistic (RL)) and closed loop supply chain (CLSC). 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 (Govindan et al., 2015; Kannan et al., 2010; Battini et al., 2017; Östlin et al., 2008; Haddadsisakht and Ryan, 2018; Sahebjamnia et al., 2018). 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 or reuse (Govindan et al., 2015; Kannan et al., 2010; Östlin et al., 2008; Haddadsisakht and Ryan, 2018; Bai and Sarkis, 2019).

Moreover, recently there have been an increasing interest in distributed recycling networks rather than centralized networks. In the following subsections a focus is made on (1) closed loop supply chain plastic recycling networks and (2) distributed recycling networks in general.

[1] https://www.plasticbank.com/.

2.2.1. An overview on closed loop supply chain in the context of plastic production and recycling

Reverse logistic and closed loop supply chains have been extensively studied in the scientific literature. Govindan et al. (2015) identified decision variables and optimization methods, among other parameters considered in these fields. They presented the level of decision variables used, which, in most cases, are operational variables (e.g. lot sizing, inventory, etc.). Also, it was found that concerning optimization methods, most studies used linear and mixed integer programming (MILP) approaches, and most consider only one optimization objective. More specifically, they found that linear programming is the dominant form of modeling for RL/CLSC problems relating to design and planning; for example, they address decisions such as facility location, facility capacity, and flow between facilities.

In the context of plastic recycling, it is possible to find in the literature a large number of articles focused on studies of RL/RSC networks (Chari et al., 2016; Hemmelmayr et al., 2013; Bing et al., 2013, 2014a,b, 2015; Hassanzadeh Amin et al., 2018; Feitó-Cespón et al., 2017; Ferri et al., 2015; Kannan et al., 2012; Wongthatsanekorn, 2009; Realff et al., 1999; Yousefi-Babadi et al., 2017; Sheriff et al., 2017). However, these types of networks are focused only on waste recovery itself, without considering how plastic waste will be reused.

According to the respective definitions of RSC and CLSC, the distributed recycling approach proposed herein corresponds to a CLSC-type network, because the plastic filament obtained from the recycling of plastic waste will be returned to the community to be used again in 3D printing. Once the products manufactured by 3D printing are discarded, they can be recovered again to repeat the recycling cycle.

Studies on plastic recycling in CLSC networks cover different aspects of it: design and planning (Kannan et al., 2009; Sheriff et al., 2014), network evaluation (Chavez and Sharma, 2018), issues and practices (French and LaForge, 2006) and uncertainty (Pati et al., 2010; Ma and Chen, 2014). Studies (Appendix A) have shown that until now, the CLSC network in the field of plastics has been considered only as centralized networks on an industrial scale. Furthermore, only two articles focus on optimization in the design and planning of the plastic recycling CLSC network. These articles correspond to studies of a centralized network, with industrial orientation and on a country level (Sheriff et al., 2014; Kannan et al., 2009). Kannan et al. (2009) propose a closed loop multi-echelon distribution inventory supply chain model, using a genetic algorithm and particle swarm optimization. The model is applied to the tire and plastic goods manufacturing industry. Alternatively, Sheriff et al. (2014) propose a mathematical model for reverse logistics, which minimizes costs and dictates the location and allocation of facilities, and transport routes. The model is applied to the plastics industry in India.

From the literature review analysis of CLSC plastic recycling networks, it could be concluded that the current research related to the logistic network design for CLSC plastic recycling only considers a centralized network on an industrial scale. This means that there seems to have been no study of a CLSC network of distributed plastic recycling to date.

From a methodological point of view, the design and planning of the CLSC approach to local and distributed plastic recycling can be studied using optimization models. Considering the literature review carried out by Govindan et al. (2015), the appropriate type of optimization model could be Mixed Integer Linear Programming (MILP), which is the most widely used.

2.2.2. Literature on distributed recycling networks

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 be dealt 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

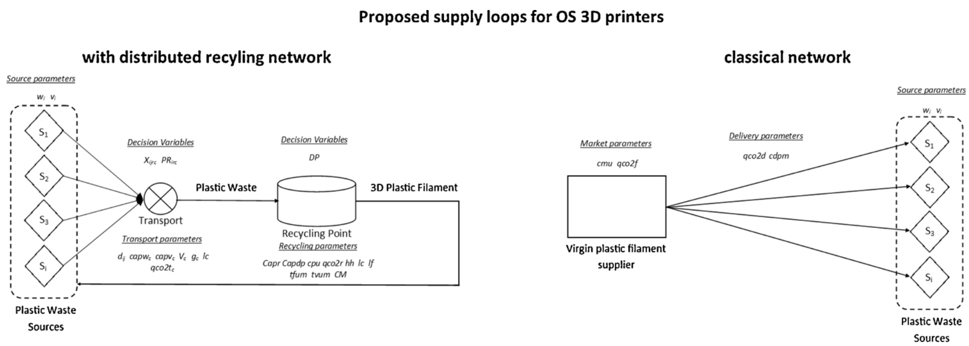


Fig. 1. Conceptual model of the recycling network.

Table 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	$i = 1, 2, \ldots, I$
Means of transport	All available means of transport in the recycling point to realize the collection.	C	$c = 1, 2, \ldots, C$
Set of routes	All available routes to realize the collection. There must be as many routes as there are plastic waste sources.	R	$r = 1, 2, \ldots, R$

Table 2
Nomenclature of decision variables.

Symbol	Description	Type 8
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

vehicles (VRP) (Rahim and Sepil, 2014).

A total of 16 articles addressing a location-routing problem for recycling were found (Appendix B). 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 a modeling perspective, the location of facilities is represented by a binary variable. The routing of vehicles is defined by means of binary variables that represent the arc between the nodes towards which the vehicle must go. Among the articles found, it is possible to identify two ways in which to understand the transport problem: (1) transport between network installations and (2) transport at the collection stage. Considering the objective function (see Table B.7 in Appendix B), it can be seen that most authors privilege minimization of costs or maximization of profit. The most considered parameters in these articles are: revenues, costs of transport (fixed and variable), operational costs of the different processes, and cost of opening facilities. In particular, revenues are considered if the collected material is sold to recycling centers or if the recycled material is sold to secondary markets. Finally, most articles use a mono-objective MILP modeling type or multi-objective modeling.

The literature on distributed recycling networks lead us to conclude that one of the most widely used methods in these approaches is the MILP model. From an economic perspective, the costs to be considered in the analysis should be: transport costs, processing costs and opening costs (the latter in the event that one of the decisions pertains to the location of facilities).

From previous analysis of the literature it can be concluded that, although the technical aspects of plastic recycling for OS 3D printing has been widely studied, no study of the logistics for the associated distributed recycling network has been undertaken. On the other hand, if we consider non distributed CLSC for plastic or distributed networks for materials other than plastic, the MILP optimization model has been well adapted and widely used to formalize this type problem. Therefore, in the next section, an MILP-type optimization model is proposed for the evaluation of the economic and environmental feasibility of the proposed distributed plastic recycling approach.

3. Model proposition

Hereafter, a CLSC network of distributed and local plastic recycling for OS 3D printing technologies is proposed. In the following subsection, the design of an optimization model to support the CLSC network definition will be developed, resulting in a corresponding mathematical model.

3.1. General aspects of the proposed model

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. 1. The context defines various fixed elements, such as:

1. A set of geographically distributed sources of polymer waste, with a

Table 3
Nomenclature of parameters.

Group	Parameter	Symbol	Units
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	$cdpm$	€/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}
	Labor cost per hour of work	lc	€/h
	Amortization cost of the machine in the period considered	CM	€
Environmental	CO_2 emitted by delivery of virgin plastic filament to the recycling point	$qCO2_d$	$kg_{CO_2}/kg_{fil.virgin}$
	CO_2 emitted per unit of virgin plastic manufactured	$qCO2_f$	kg_{CO_2}/kg_{virgin}
	CO_2 emitted per unit of plastic recycled	$qCO2_r$	kg_{CO_2}/kg_{recy}
	CO_2 emitted by the means of transport c	$qCO2_t$	kg_{CO_2}/km

Table 4
Parameters considered for the case study.

Group	Parameter	Value	Reference
Means of transport	Car capacity (volume)	254 L	Suzuki Celerio (Suzuki Motor Corporation, 2018a)
	Car capacity (kg)	415 kg	Suzuki Celerio (Suzuki Motor Corporation, 2018a)
	Car speed	71 km/h	Average speed between cities using Google maps (Appendix F)
	Variable cost of the car (gasoline and amortization)	0.15€/km	LF2L
	Motorcycle capacity including box (volume)	78 L	Suzuki Burgman 125 cc (Suzuki Motor Corporation, 2018b)
	Motorcycle capacity including box (kilograms)	17 kg	Estimation based on weight-volume relation (4.58 L/kg).
	Motorcycle speed	71 km/h	Average speed between cities using Google maps (Appendix F)
	Variable cost of the motorcycle (gasoline and amortization)	€0.15/km	LF2L
Recycling point	Daily recycling capacity	4.9 kg/day	LF2L
	Capacity of recycling in the period considered	98 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
Economical	Amortization cost of the machine	€250/month	LF2L
	Cost of purchase of plastic filament	€30.47/kg	(3ders, 2019)
	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	(Zhao et al., 2018)
	Price of CO_2 emission	€20/ton	(Bing et al., 2014a)
	Labor cost	€17/h	LF2L
Environmental	CO_2 emitted by manufacturing virgin plastic	1.8 kg of CO_2 eq./kg of plastic	(Vink et al., 2003)
	CO_2 emitted by plastic recycling	0.52 kg of CO_2 eq./kg of plastic waste	(Kreiger et al., 2014)
	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	(Dekker et al., 2012)
	Emission of delivery transport of plastic filament	4.229 kg of CO_2/kg of plastic	(Dekker et al., 2012)
	Car emissions	99 g of CO_2/km	Suzuki Celerio (Suzuki Motor Corporation, 2018a)
	Motorcycle emissions	68 g of CO_2/km	Suzuki Burgman 125 cc (Suzuki Moto France, 2018)

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

Table 5
Results.

Index	Value
Total benefit (€)	317.8
Economic benefit (€)	315.3
Total alternative cost (€)	789.8
Total cost of delivery plastic filament (€)	Not considered
Total cost of transport (€)	57.5
Total labor cost of transport (€)	91.7
Total cost of processing (€)	25.3
Total labor cost of processing (€)	50
Amortization cost of the machine (€)	250
Environmental benefit (€)	2.4
Total cost of emissions by fabrication (€)	1.0
Total cost of emissions by delivery of plastic filament (€)	2.4
Total cost of emissions by recycling (€)	0.3
Total cost of emission by transport (€)	0.8
Amount collected (kg)	28.8
Amount available (kg)	28.8
Number of points available for collection	19
Number of points collected	19
Processing days	6
Number of routes	1
Total distance traveled (km)	383
Total motorcycle distance (km)	0
Total car distance (km)	383
CO_2 saving (kg)	120.7
Relative gap	0.09
Absolute gap	30.13
Best possible	347.85
Final solve	317.72
Resource usage (s)	7200

relatively "clean" plastic waste (Cruz Sanchez, 2016) is collected and transported from the various sources. 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. 1).

3.2. Model formalization

The nomenclature used for the representation of sets, decision variables and parameters, are presented in Tables 1–3 respectively.

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

3.2.1. 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.

Therefore, as this involves a mono-objective modeling, mathematically the objective function is modeled as a maximization of the sum of economic benefit and environmental benefit.

3.2.2. 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

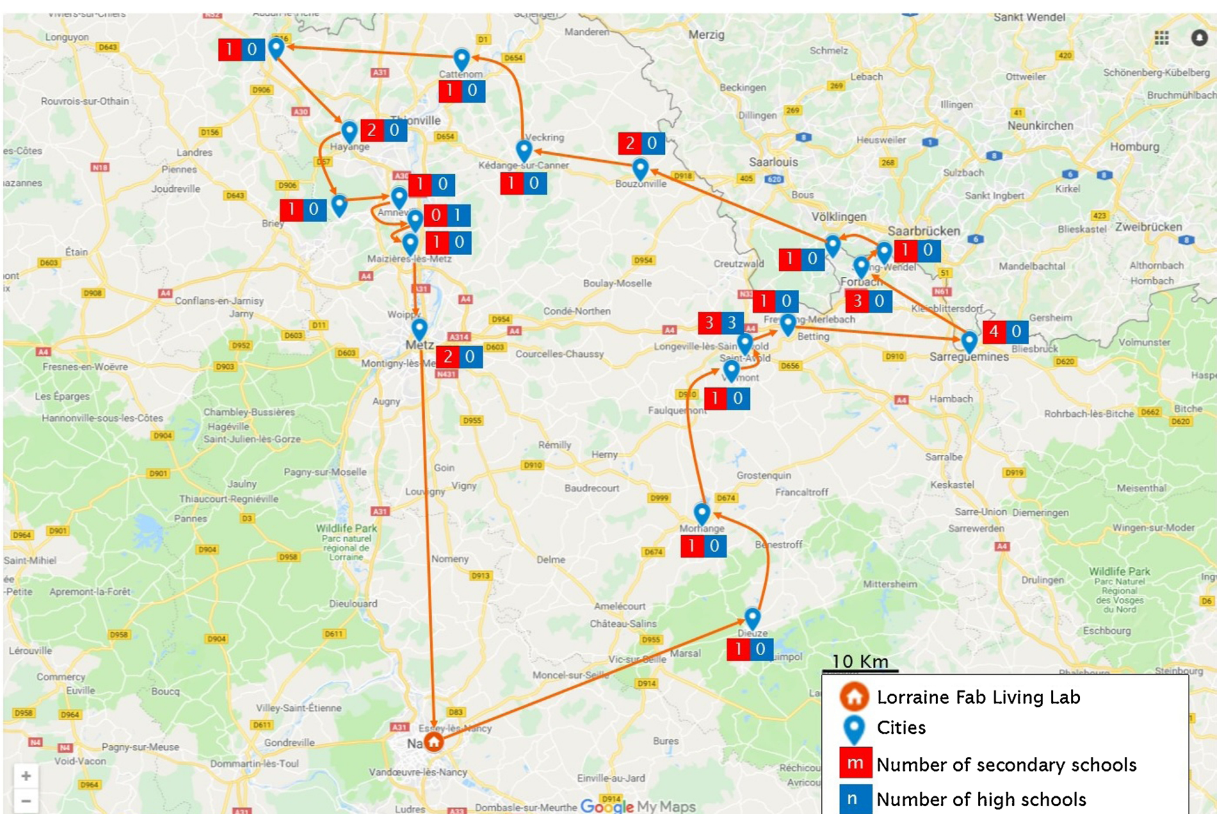
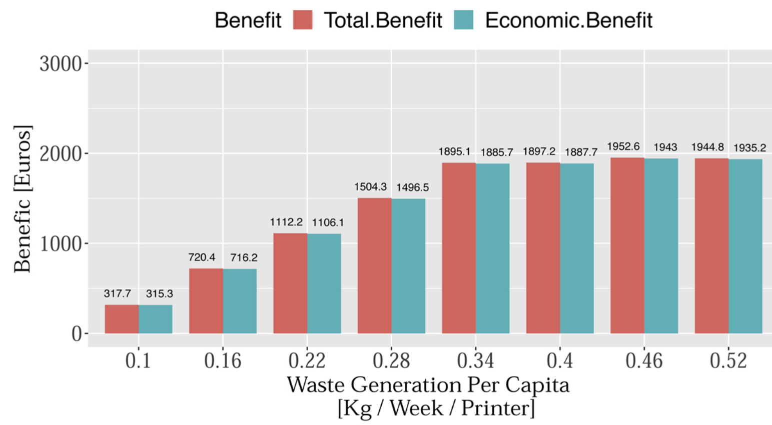
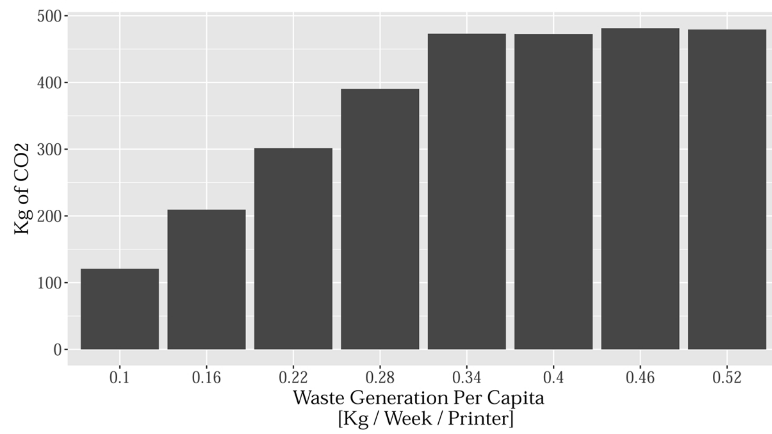


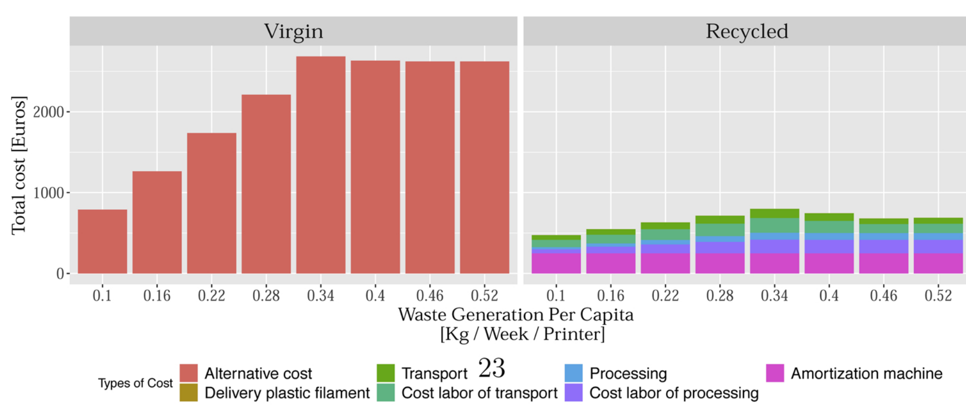
Fig. 2. Solution map.



(a) Model sensitivity analysis with variation of the quantity of plastic waste per printer.



(b) CO_2 saving by variation of the quantity of plastic waste per printer



(c) Comparison of the total cost between Virgin and Recycled plastic

Fig. 3. (a) Model sensitivity analysis with variation of the quantity of plastic waste per printer. (b) CO_2 saving by variation of the quantity of plastic waste per printer. (c) Comparison of the total cost between virgin and recycled plastic.

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 Fig. 1:

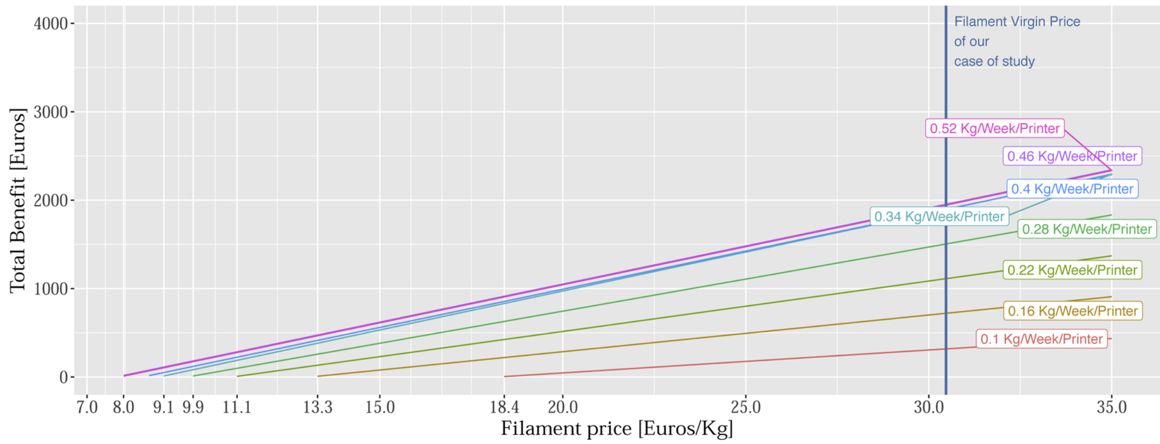


Fig. 4. Model sensitivity analysis with variation of plastic filament price.

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

3.2.3. Environmental benefit

The environmental benefit corresponds to the quantity of carbon dioxide emissions avoided as a result of recycling a quantity of plastic, expressed in monetary units (Bing et al., 2014a; Haddadsisakht and Ryan, 2018). 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):

$$\begin{aligned}\text{Environmental Benefit} &= \left(\sum_{i\in I}\sum_{c\in C}\sum_{r\in R} w_i{*}\text{PR}_{\text{irc}}{*}\text{pem}{*}(\text{qCO2}_f+\text{qCO2}_d)\right)\\ &\quad-\left(\sum_{i\in I}\sum_{j\in I}\sum_{c\in C}\sum_{r\in R} x_{\text{ijrc}}{*}d_{\text{ij}}{*}\text{qCO2}_t{*}\text{pem}+\sum_{i\in I}\sum_{c\in C}\sum_{r\in R} w_i{*}\text{PR}_{\text{irc}}{*}\text{qCO2}_r\right.\\ &\quad\left.{*}\text{pem}\right)\end{aligned} \tag{2}$$

3.3. 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.

3.3.1. Route restrictions

Route restrictions are considered in order to integrate characteristics into the routes generated by the modeled solution.

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:

$$\sum_{c\in C}\sum_{r\in R}\text{PR}_{\text{irc}}\le 1 \quad \forall\, i\in I-\{\text{Recycling Point}\} \tag{3}$$

$$\begin{aligned}\text{DR}_{\text{jrc}}=\text{PR}_{\text{irc}} \quad &\forall\, c\in C,\quad \forall\, r\in R,\\ &\forall\, i\in I-\{\text{Recycling Point}\},\quad \forall\, j\in I-\{\text{Recycling Point}\},\quad i=j\end{aligned} \tag{4}$$

$$\sum_{j\in I} x_{\text{ijrc}}=\text{PR}_{\text{irc}} \quad \forall\, c\in C,\quad \forall\, r\in R,\quad \forall\, i\in I-\{\text{Recycling Point}\} \tag{5}$$

$$\sum_{i\in I} x_{\text{ijrc}}=\text{DR}_{\text{jrc}} \quad \forall\, c\in C,\quad \forall\, r\in R,\quad \forall\, j\in I-\{\text{Recycling Point}\} \tag{6}$$

$$\sum_{j\in I}\sum_{c\in C} x_{\text{ijrc}}\le 1 \quad \forall\, r\in R,\quad \forall\, i\in I-\{\text{Recycling Point}\} \tag{7}$$

$$\sum_{i\in I}\sum_{c\in C} x_{\text{ijrc}}\le 1 \quad \forall\, r\in R,\quad \forall\, j\in I-\{\text{Recycling Point}\} \tag{8}$$

$$\begin{aligned}U_i-U_j+n{*}x_{\text{ijrc}}\le n-1 \quad &\forall\, r\in R,\\ &\forall\, i\in I-\{\text{Recycling Point}\},\quad \forall\, j\in I-\{\text{Recycling Point}\},\quad i,j\\ &=1,\ldots,n\end{aligned} \tag{9}$$

3.3.2. Restrictions on means of transport

Restrictions on means of transport are considered in order to integrate their characteristics into the model solution.

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:

$$\sum_{i\in I} w_i{*}\text{PR}_{\text{irc}}\le \text{capw}_c \quad \forall\, r\in R,\quad \forall\, c\in C \tag{10}$$

$$\sum_{i \in I} v_i * \mathrm{PR}_{\mathrm{irc}} \leq \mathrm{capv}_c \quad \forall\ r \in R, \quad \forall\ c \in C \tag{11}$$

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

3.3.3. 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.

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:

$$\sum_{i \in I} \sum_{r \in R} \sum_{c \in C} w_i * \mathrm{PR}_{\mathrm{irc}} \leq \mathrm{Capr} \tag{13}$$

$$\sum_{i \in I} \sum_{r \in R} \sum_{c \in C} \frac{w_i * \mathrm{PR}_{\mathrm{irc}}}{\mathrm{Capdp}} \leq \mathrm{DP} \tag{14}$$

$$\sum_{i \in I} \sum_{r \in R} \sum_{c \in C} \frac{w_i * \mathrm{PR}_{\mathrm{irc}}}{\mathrm{Capdp}} + 1 \geq \mathrm{DP} \tag{15}$$

3.3.4. 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 Eqs. (1) and (2) respectively) do not take negative values. Eq. (18) represents binary constraints. Eqs. (19) and (20) are non-negative constraints:

$$\text{Economic Benefit} \geq 0 \tag{16}$$

$$\text{Environmental Benefit} \geq 0 \tag{17}$$

$$x_{\mathrm{ijrc}}, \mathrm{PR}_{\mathrm{irc}}, \mathrm{DR}_{\mathrm{jrc}}\text{: binary} \quad \forall\ i \in I, \quad \forall\ j \in I, \quad \forall\ r \in R, \quad \forall\ c \in C \tag{18}$$

$$U_i \geq 0 \quad \forall\ i \in I \tag{19}$$

$$\mathrm{DP} \geq 0 \tag{20}$$

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. Case study: Lorraine Fab Living Lab

The case study of the Lorraine Fab Living Lab (LF2L),[2] a platform integrating several 3D printing and extrusion devices, located in Nancy, France, is presented. The pilot recycling process has been implemented within the facilities of the LF2L, following the process flow described in the work of Cruz Sanchez et al. (2017). The LF2L is considering the possibility of implementing this recycling process on its premises. Moreover, 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 program (Robine and Tomasini, 2018). This provides an opportunity to explore the feasibility of the distributed CLSC plastic recycling network using the LF2L as recycling point.

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 technical high schools of the Lorraine region, based on information obtained in relation to secondary schools already using 3D printers. To address the feasibility thereof, the following assumptions were considered:

- For secondary schools a quantity of 2 printers and for the high schools a quantity of 4 printers are considered.
- A quantity of 100 g of PLA plastic waste per printer per week is considered. This is the minimum value already reported by several secondary school teachers. Moreover, they are currently the lead users in their institutions and they claim that this amount will be higher in the near future, as more and more colleagues will use this technology in their academic programs.
- A volume of 4.58 L/kg of PLA plastic waste is considered. This value was obtained by weighing a cardboard box (8.5 cm × 22 cm × 23.5 cm) containing different pieces printed with PLA (959 grams). The pieces considered in the estimation correspond to pieces used in the field of education (see Appendix C).
- Collection will be undertaken on a monthly basis.

The monthly PLA plastic waste obtained from every city considered is presented in Appendix Table D.8. The other parameters used in the model are shown in Table 4. The calculation of distances between cities is shown in Appendix E.

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 restrictions (IBM, 2019)) and the current best integer solution (GAMS, 2018; Grossmann et al., 2003). 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 (GAMS, 2018; Grossmann et al., 2003).

The results of the solution obtained for the objective function (Eq. (1) and Eq. (2)) and the parameters of the model (Table 4) are shown in Table 5. A time tolerance of two hours of calculation was used. A total benefit of €317.8 per month was obtained, which corresponds to the sum of the monthly economic benefit and environmental benefit, with values of €315.3 per month and €2.4 per month respectively. Considering the optimization method used (IBM, 2019), the result obtained has a 9% relative gap. Therefore, is not possible to guarantee that the best solution found by the algorithm, after two hours of calculation, is a global optimal.

The total amount of PLA plastic waste to be collected is 28.8 kg per month. This plastic is collected over a total distance of 383 km. All this operation enables us to stop emitting 120.7 kg of CO_2, corresponding to a CO_2 reduction of 69.5% 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 19 selected cities out of 19 potential cities. To perform the collection, the model solution proposes the route shown in Fig. 2. Only one car is needed to perform the collection using

[2] A project called Green Fablab (http://lf2l.fr/projects/green-fablab/) is being developed.

the route shown in Fig. 2.

5.1. 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.

5.1.1. Variation of plastic waste per printer quantity

The model was executed repeatedly by varying the amount of PLA waste per printer per week by 0.06 kg to reach 0.34 kg, where it is estimated that the maximum recycling capacity is reached. Then, the amount was varied in the same quantity to reach 0.52 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. 3a. The details of the results and GAMS output information are presented in Appendix G.

Looking at the results shown in Fig. 3, we can see 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.

If we consider the amount of emissions of CO_2 (Fig. 3b) reduced, we can see that the amount of CO_2 saved increases until we reach 0.34 kg of PLA waste per printer per week. Thereafter, the amount of CO_2 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 capacity of the LF2L by collecting waste from the nearest points.

Considering the economic aspects, costs specifically (Fig. 3c), 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.

5.1.2. 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 (€30.47 per kilogram) was changed and combined with the different solutions obtained, varying the quantity of plastic waste per printer considered in Section 5.1.1. The results obtained are shown in Fig. 4.

In the first results, we can see that, when considering 0.1 kg of PLA per printer per week to be recycled, there will only be a benefit if the purchase price remains higher than 18.4 euros per kilogram. Therefore, if the recycling quantity per printer changes, we will observe a benefit if the purchase price is greater than 8 euros per kilogram. This limit was installed by the Lorraine Fab Living Lab full recycling capacity.

6. 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 feasibility. 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 by over 50% the CO_2 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 worldwide (Fablabconnect, 2019)) 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 other models in the literature, this model has been developed in a simple way, in order to analyze the economic and environmental feasibility 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 feasibility 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 needs 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 explore further. 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.

7. Conclusions and perspectives

This work has demonstrated the economic and environmental feasibility of a distributed closed loop supply chain network for plastic recycling using OS 3D printing technologies.

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. This network could furthermore act in parallel with the large-scale plastic recycling industry in order to increase the rate of plastic recycling.

The present work considers only economic and environmental dimensions. However, this type of analysis needs to consider social and political aspects. These aspects could be considered in future works by means of, for example, multi-objective modeling. Moreover, uncertainty regarding available plastic waste, and the optimal location of one or many recycling facilities in accordance with the capacities of recycling facilities, should be considered in the model. Replication of this network in different contexts and comparison thereof would also be useful.

Conflict of interest

None declared.

Appendix A. Analysis of works in the area of plastics, closed loop supply chain

Table A.6.

Table A.6
Analysis of works in the area of plastics, closed loop supply chain.

Author	Area of the study of the network	Orientation	Network type	Description
Kannan et al. (2009)	Design and planning	Industrial	Centralized	Propose a closed loop multi-echelon distribution inventory supply chain model, which solves by means of a genetic algorithm and particle swarm optimization. The model is applied in the cases of the tire manufacturing industry and the plastic goods manufacturing industry.
Sheriff et al. (2014)	Design and planning	Industrial	Centralized	Propose a mathematical model for reverse logistics, which minimizes costs and decides the location of facilities, the allocation of facilities, and the transport routes. The model is applied to the case of the plastics industry in India.
French and LaForge (2006)	Issues and practices	Industrial	Centralized	Exploratory analysis of the reuse practices of the process industry (including plastic) in a CLSC network. From these results it is concluded that "research efforts are needed in the areas of network design and product acquisition; inventory; production planning and control; and scheduling."
Chavez and Sharma (2018)	Network evaluation	Industrial	Centralized	Evaluate and compare the profitability and environmental friendliness of a CLSC chemical PET recycling network. A case study of the Mexican automotive market is evaluated from the point of view of cost, energy consumption, and CO_2 emissions, based on a PESTEL analysis. Comparing these results with a forward network, it showed that the proposed CLSC network is more profitable (the recycled plastic can be sold to Japan with a margin of 4.24%) and environmentally friendly (reducing energy consumption by 79% and the CO_2 generated by 73%).
Ma and Chen (2014)	Uncertainty	Industrial	Centralized	Model and analyze the play of three oligarch retailers in a CLSC network by means of Nash equilibrium, bifurcation, and chaos of e.g. the recycling price. As a case for modeling, they consider that retailers recycle the products, send them to the manufacturer for repair and then resell them as a secondhand product in conjunction with the new products. These secondhand products have the same performance and appearance as the new products, but a different degree of customer acceptance, which affects their price.
Pati et al. (2010)	Uncertainty	Industrial	Centralized	Measure the bullwhip effect in a closed loop supply chain network, i.e. the effect of demand variability in a CLSC network.

Appendix B. Literature on distributed recycling networks

Table B.7
Literature on distributed recycling networks

Author	Type of optimization model	Objective function	Economic parameters					
			Revenues	Cost of transport	Operational/processing cost	Cost of opening facilities	Inventory cost	Incentive cost
Asefi et al. (2019)	Mixed integer linear programming	Min cost		x		x		
Aydemir-Karadag (2018)	Mixed integer linear programming	Max profit	x	x		x		
Aka and Akyüz (2018)	Multi-objective	Max number of containers and Min distance between containers						
Farrokhi-Asl et al. (2018)	Multi-objective	Min cost, Min risk during transportation and Min risk in facilities		x		x		
Asefi et al. (2017)	Mixed integer linear programming	Min cost	x			x		
Hemmelmayr et al. (2017)	Mixed integer programming	Min cost		x		x		
Zhao and Ke (2017)	Multi-objective	Min cost, Min risk during transportation and Min risk of inventory		x	x	x	x	
Yu and Solvang (2016)	Multi-objective	Min cost, Min risk during transportation and Min risk in facilities		x	x	x		
Vidović et al. (2016)	Mixed integer linear programming	Max profit	x	x		x		
Ghezavati and Morakabatchian (2013)	Multi-objective	Min cost, Min risk during transportation and Min risk in facilities		x	x	x		
Asefi et al. (2015)	mixed integer linear programming	Min cost		x		x		
Zhao and Huang (2015)	Multi-objective	Min cost, Min risk during transportation and Min risk in facilities		x		x		
Rahim and Sepil (2014)	Mixed integer linear programming	Max profit	x	x				
Sheriff et al. (2014)	Mixed integer linear programming	Min cost		x	x	x		x
Boyer et al. (2013)	Multi-objective	Min cost and Min risk of transport		x	x	x		
Samanlioglu (2013)	Multi-objective	Min cost, Min risk during transportation and Min risk in facilities		x	x			

Appendix C. Pieces considered for weight-volume estimation

Fig. C.5.

Fig. C.5. Pieces considered for weight-volume estimation.

Appendix D. Amount of PLA plastic waste per city

Table D.8
Amount of PLA plastic waste per city.

City	Number of secondary schools	Number of high schools	Kilograms of monthly PLA plastic waste
Amneville	1	0	0.8
Aumetz	1	0	0.8
Bouzonville	2	0	1.6
Cattenom	1	0	0.8
Dieuze	1	0	0.8
Folschviller	1	0	0.8
Forbach	3	0	2.4
Hayange	2	0	1.6
Hombourg Haut	1	0	0.8
Kedange Sur Canner	1	0	0.8
Maizieres Les Metz	1	0	0.8
Metz	2	0	1.6
Morhange	1	0	0.8
Moyeuvre Grande	1	0	0.8
Petite Rosselle	1	0	0.8
Sarreguemines	4	0	3.2
St Avold	3	3	7.2
Stiring Wendel	1	0	0.8
Talange	0	1	1.6

Appendix E. Distance between cities (km)

Table E.9.

Table E.9
Distance between cities (km) based on Google Map.

	LF2L	Amneville	Aumetz	Bouzonville	Cattenom	Dieuze	Folschviller	Forbach	Hayange	Hombourg Haut
LF2L	0	76	101	96	95	43	66	111	84	106
Amneville	75	0	31	37	26	86	67	75	14	70
Aumetz	101	31	0	55	27	111	92	100	18	95
Bouzonville	96	37	55	0	31	71	35	55	42	36
Cattenom	95	26	26	31	0	105	86	94	18	89
Dieuze	43	85	110	71	103	0	40	55	94	44
Folschviller	67	66	92	35	85	40	0	26	75	13
Forbach	111	73	99	54	92	56	26	0	82	14
Hayange	84	14	15	42	18	94	75	84	0	78
Hombourg Haut	105	67	92	48	85	43	13	14	76	0
Kedange Sur Canner	89	21	38	19	16	96	52	69	25	63
Maizieres Les Metz	68	8	37	37	30	78	59	67	20	62
Metz	59	21	47	36	40	67	50	59	30	54
Morhange	48	70	95	54	88	17	23	50	78	37
Moyeuvre Grande	79	9	34	47	35	89	70	78	14	73
Petite Rosselle	115	77	103	34	96	59	30	5	86	17
Sarreguemines	89	95	120	76	113	49	36	24	104	34
St Avold	74	61	86	30	79	39	7	21	70	7
Stiring Wendel	115	77	103	42	96	59	30	4	86	17
Talange	70	5	33	36	26	81	61	70	17	65

	Kedange Sur Canner	Maizieres Les Metz	Metz	Morhange	Moyeuvre Grande	Petite Rosselle	Sarreguemines	St Avold	Stiring Wendel	Talange
LF2L	88	69	57	48	80	115	89	74	115	71
Amneville	20	8	21	71	9	78	95	62	79	5
Aumetz	38	36	47	96	33	104	121	87	104	33
Bouzonville	19	43	43	54	47	36	58	32	41	36
Cattenom	16	30	41	90	35	82	115	81	98	27
Dieuze	93	79	66	17	89	58	49	39	59	80
Folschviller	52	61	50	23	71	30	36	7	30	61
Forbach	69	68	57	50	78	5	24	22	4	69
Hayange	26	20	30	79	13	87	104	71	87	16
Hombourg Haut	62	61	51	37	72	17	34	8	17	62
Kedange Sur Canner	0	23	29	63	31	55	89	48	72	19
Maizieres Les Metz	23	0	14	63	14	71	88	55	71	3
Metz	29	15	0	51	26	62	79	46	63	17
Morhange	63	64	51	0	74	54	41	30	54	65
Moyeuvre Grande	31	13	25	74	0	82	99	66	82	13
Petite Rosselle	72	72	61	54	82	0	30	25	8	72
Sarreguemines	89	89	79	41	99	30	0	43	28	90
St Avold	55	55	45	31	65	24	41	0	25	56
Stiring Wendel	72	72	61	54	82	8	28	25	0	72
Talange	19	3	17	66	13	73	90	57	74	0

Appendix F. Mean speed between cities (km/h) based on Google Map

Table F.10.

Table F.10
Speed between cities (km/h).

	LF2L	Amneville	Aumetz	Bouzonville	Cattenom	Dieuze	Folschviller	Forbach	Hayange	Hombourg Haut
LF2L	0	79	87	80	80	57	59	89	84	87
Amneville	76	0	72	53	56	75	80	88	53	86
Aumetz	84	74	0	67	58	82	89	95	72	93
Bouzonville	79	54	67	0	56	65	57	79	63	55
Cattenom	77	52	58	55	0	76	81	87	45	85
Dieuze	57	76	83	62	77	0	63	63	82	61
Folschviller	60	81	89	55	81	65	0	60	87	56
Forbach	86	88	96	75	88	63	58	0	95	56
Hayange	83	60	45	63	47	81	88	97	0	94
Hombourg Haut	86	89	95	74	86	60	60	60	95	0
Kedange Sur Canner	74	47	67	57	46	73	58	74	60	70
Maizieres Les Metz	77	44	82	54	64	77	82	91	71	89
Metz	72	55	81	57	69	69	73	86	75	81
Morhange	59	78	85	64	78	57	58	68	82	69
Moyeuvre Grande	74	45	76	58	60	74	79	87	49	84
Petite Rosselle	85	87	94	51	86	62	60	33	92	54
Sarreguemines	60	92	96	81	89	60	55	72	96	73
St Avold	63	87	94	55	85	62	47	66	93	53
Stiring Wendel	88	92	98	61	90	67	67	27	99	64
Talange	81	30	86	57	65	80	85	95	78	93

	Kedange Sur Canner	Maizieres Les Metz	Metz	Morhange	Moyeuvre Grande	Petite Rosselle	Sarreguemines	St Avold	Stiring Wendel	Talange
LF2L	75	78	76	58	75	86	59	63	91	82
Amneville	44	40	53	73	42	84	89	81	91	30
Aumetz	69	80	76	82	71	92	96	90	98	83
Bouzonville	57	68	72	65	59	55	62	56	62	57
Cattenom	46	62	63	75	58	75	88	81	88	62
Dieuze	72	78	69	54	74	61	60	62	67	77
Folschviller	58	83	75	55	77	56	55	47	64	83
Forbach	74	93	86	65	85	27	69	60	30	94
Hayange	62	75	72	80	52	92	96	91	98	74
Hombourg Haut	72	92	85	67	85	51	73	48	64	93
Kedange Sur Canner	0	49	54	60	56	56	77	56	74	48
Maizieres Les Metz	51	0	49	74	47	87	93	85	95	36
Metz	54	53	0	65	56	79	86	75	88	64
Morhange	61	78	68	0	74	65	57	67	70	80
Moyeuvre Grande	55	46	52	73	0	83	89	81	88	41
Petite Rosselle	72	90	83	66	83	0	64	58	40	90
Sarreguemines	77	94	89	57	87	64	0	74	76	95
St Avold	67	89	82	66	81	58	75	0	71	91
Stiring Wendel	76	96	89	70	88	40	73	65	0	96
Talange	50	36	60	78	41	89	95	88	99	0

Appendix G. Results of variation of the plastic waste per printer quantity

Table G.11.

Table G.11
Results of variation of the plastic waste per printer quantity.

	0.10 kg	0.16 kg	0.22 kg	0.28 kg	0.34 kg	0.40 kg	0.46 kg	0.52 kg
Total benefit (€)	317.72	720.37	1112.16	1504.31	1895.12	1897.19	1952.62	1944.79
Economic benefit (€)	315.30	716.19	1106.13	1496.50	1885.67	1887.74	1943.00	1935.21
Total alternative cost (€)	789.78	1263.65	1737.52	2211.39	2685.26	2632.61	2623.83	2623.83
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 (€)	57.45	67.50	83.40	97.50	113.70	93.90	69.45	72.45
Total cost of processing (€)	25.34	40.55	55.76	70.96	86.17	84.48	84.20	84.20
Total labor cost of transport (€)	91.70	107.75	133.13	155.63	181.49	149.89	110.86	115.65
Total labor cost of processing (€)	49.98	81.67	109.11	140.79	168.23	166.60	166.33	166.33
Amortization cost of the machine (€)	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
Environmental benefit (€)	2.41	4.19	6.03	7.81	9.46	9.45	9.63	9.59
Total cost of emissions by fabrication (€)	1.04	1.66	2.28	2.90	3.53	3.46	3.44	3.44
Total cost of emissions by delivery of plastic filament (€)	2.44	3.90	5.36	6.82	8.28	8.12	8.09	8.09
Total cost of emissions by recycling (€)	0.30	0.48	0.66	0.84	1.02	1.00	1.00	1.00
Total cost of emissions by transport (€)	0.76	0.89	0.95	1.08	1.33	1.13	0.92	0.96
CO2 saving (kg)	120.74	209.30	301.45	390.28	472.92	472.50	481.26	479.28
Possible collection points	19	19	19	19	19	19	19	19
Points selected by the model	19	19	19	19	19	14	11	9
Amount available (kg)	28.80	46.08	63.36	80.64	97.92	115.20	132.48	149.76
Amount collected (kg)	28.80	46.08	63.36	80.64	97.92	96.00	95.68	95.68
Processing days	6	10	13	17	20	20	20	20
Number of routes	1	1	2	3	3	3	2	2
Number of routes of the car	1	1	1	1	2	2	2	2
Number of routes of the motorcycle	0	0	1	2	1	1	0	0
Total distance traveled (km)	383	450	556	650	758	626	463	483
Total motorcycle distance (km)	0	0	240	335	275	181	0	0
Total car distance (km)	383	450	316	315	483	445	463	483
Relative gap	0.09	0.08	0.08	0.08	0.08	0.08	0.06	0.07
Absolute gap	30.13	64.33	98.14	127.11	170.30	168.89	124.11	146.03
Best possible	347.85	784.70	1210.30	1631.42	2065.42	2066.08	2076.73	2090.82
Final solve	317.72	720.37	1112.16	1504.31	1895.12	1897.19	1952.62	1944.80
Resource usage (s)	7200.00	292.22	13,097.95	26,741.44	11,518.11	4293.09	100.22	326.72

References

3ders, 2019. Price Compare – 3D Printing Materials – Filament. http://www.3ders.org/pricecompare/?o=Priceperkg&m=PLA&d=1.75&w=1&sc=USA (last checked on 01.1.18).

Aka, S., Akyüz, G., 2018. Fuzzy goal programming approach on location-routing model for waste containers. Int. J. Ind. Syst. Eng. 29, 413–427.

Asefi, H., Lim, S., Maghrebi, M., 2015. A mathematical model for the municipal solid waste location-routing problem with intermediate transfer stations. Aust. J. Inform. Syst. 19, S21–S35.

Asefi, H., Lim, S., Maghrebi, M., 2017. Adaptation of simulated annealing to an integrated municipal solid waste location-routing problem. Int. J. Logist. Syst. Manag. 28, 127–143.

Asefi, H., Lim, S., Maghrebi, M., Shahparvari, S., 2019. Mathematical modelling and heuristic approaches to the location-routing problem of a cost-effective integrated solid waste management. Ann. Oper. Res. 273, 75–110.

ASTM & ISO, 2015. Standard Terminology for Additive Manufacturing – General Principles – Terminology.

Aydemir-Karadag, A., 2018. A profit-oriented mathematical model for hazardous waste locating-routing problem. J. Clean. Prod. 202, 213–225.

Baechler, C., DeVuono, M., Pearce, J.M., 2013. Distributed recycling of waste polymer into RepRap feedstock. Rapid Prototyp. J. 19, 118–125.

Bai, C., Sarkis, J., 2019. Integrating and extending data and decision tools for sustainable third-party reverse logistics provider selection. Comput. Oper. Res. 110, 188–207. https://doi.org/10.1016/j.cor.2018.06.005.

Battini, D., Bogataj, M., Choudhary, A., 2017. Closed loop supply chain (CLSC): economics, modelling, management and control. Int. J. Prod. Econ. 183, 319–321.

Bikas, H., Stavropoulos, P., Chryssolouris, G., 2016. Additive manufacturing methods and modelling approaches: a critical review. Int. J. Adv. Manuf. Technol. 83, 389–405.

Bing, X., Groot, J., Bloemhof-Ruwaard, J., van der Vorst, J., 2013. Multimodal network design for sustainable household plastic recycling. Int. J. Phys. Distrib. Logist. Manag. 43, 452–477.

Bing, X., Bloemhof-Ruwaard, J.M., van der Vorst, J.G.A.J., 2014a. Sustainable reverse logistics network design for household plastic waste. Flex. Serv. Manuf. J. 26, 119–142.

Bing, X., Bloemhof-Ruwaard, J., van der Vorst, J., 2014b. Sustainable reverse logistics network design for household plastic waste. Flex. Serv. Manuf. J. 26, 119–142.

Bing, X., Bloemhof-Ruwaard, J., Chaabane, A., Van Der Vorst, J., 2015. Global reverse supply chain redesign for household plastic waste under the emission trading scheme. J. Clean. Prod. 103, 28–39.

Bogers, M., Hadar, R., Bilberg, A., 2016. Additive manufacturing for consumer-centric business models: implications for supply chains in consumer goods manufacturing. Technol. Forecast. Soc. Change 102. https://doi.org/10.1016/j.techfore.2015.07.024.

Boyer, O., Sai Hong, T., Pedram, A., Mohd Yusuff, R.B., Zulkifli, N., 2013. A mathematical model for the industrial hazardous waste location-routing problem. J. Appl. Math. 2013, 1–10.

Braanker, G.B., Flohil, J.J., Tokaya, G.E., 2010. Developing a Plastics Recycling Add-On for the RepRap 3D Printer (Ph.D. thesis). Defl University of Technology.

Chari, N., Venkatadri, U., Diallo, C., 2016. Design of a reverse logistics network for recyclable collection in Nova Scotia using compaction trailers. INFOR 54, 1–18.

Chavez, R., Sharma, M., 2018. Profitability and environmental friendliness of a closed-loop supply chain for PET components: a case study of the Mexican automobile market. Resour. Conserv. Recycl. 135, 172–189.

Cruz Sanchez, F.A., 2016. Methodological Proposition to Evaluate Polymer Recycling in Open-Source Additive Manufacturing Contexts. Chemical and Process Engineering, Université de Lorraine.

Cruz Sanchez, F.A., Boudaoud, H., Hoppe, S., Camargo, M., 2017. Polymer recycling in an open-source additive manufacturing context: mechanical issues. Addit. Manuf. 17, 87–105.

Cruz Sanchez, F.A., Boudaoud, H., Muller, L., Camargo, M., 2014. Towards a standard experimental protocol for open source additive manufacturing. Virtual Phys. Prototyp. 9, 151–167.

Cruz Sanchez, F.A., Lanza, S., Boudaoud, H., Hoppe, S., Camargo, M., 2015. Polymer recycling and additive manufacturing in an open source context: optimization of processes and methods. Proceedings of Solid Freeform Fabrication Symposium 1591–1600.

Dekker, R., Bloemhof, J., Mallidis, I., 2012. Operations Research for green logistics – an overview of aspects, issues, contributions and challenges. Eur. J. Oper. Res. 219, 671–679.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S., Garmulewicz, A., Knowles, S., Minshall, T., Mortara, L., Reed-Tsochas, F., Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: a research agenda. Technol. Forecast. Soc. Change 115, 75–84.

EU Commission, 2018. A European Strategy for Plastics in a Circular Economy.

Fablabconnect, 2019. 1,600 Fab Labs Worldwide!. https://www.fablabconnect.com/1600-fab-labs-worldwide/ (last checked on 22.04.19).

Farrokhi-Asl, H., Makui, A., Jabbarzadeh, A., Barzinpour, F., 2018. Solving a multi-objective sustainable waste collection problem considering a new collection network. Oper. Res.

Feitó-Cespón, M., Sarache, W., Piedra-Jimenez, F., Cespón-Castro, R., 2017. Redesign of a sustainable reverse supply chain under uncertainty: a case study. J. Clean. Prod. 151, 206–217.

Ferri, G., Diniz Chaves, G., Ribeiro, G., 2015. Reverse logistics network for municipal solid waste management: the inclusion of waste pickers as a Brazilian legal requirement. Waste Manag. 40, 173–191.

French, M.L., LaForge, R.L., 2006. Closed-loop supply chains in process industries: an empirical study of producer re-use issues. J. Oper. Manag. 24, 271–286.

GAMS, 2018. GAMS – Documentation.

Gardan, J., 2016. Additive manufacturing technologies: state of the art and trends. Int. J. Prod. Res. 54, 3118–3132.

Garmulewicz, A., Holweg, M., Veldhuis, H., Yang, A., Disruptive, 2018. Technology as an enabler of the circular economy: what potential does 3D printing hold? Calif. Manag. Rev. 60, 112–132.

Ghezavati, V., Morakabatchian, S., 2015. Application of a fuzzy service level constraint for solving a multi-objective location-routing problem for the industrial hazardous wastes. J. Intell. Fuzzy Syst. 28, 2003–2013.

González-Henríquez, C.M., Sarabia-Vallejos, M.A., Rodriguez-Hernandez, J., 2019. Polymers for additive manufacturing and 4D-printing: materials, methodologies, and biomedical applications. Prog. Polym. Sci. 94, 57–116. https://doi.org/10.1016/j.progpolymsci.2019.03.001.

Govindan, K., Soleimani, H., Kannan, D., 2015. Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future. Eur. J. Oper. Res. 240, 603–626.

Grossmann, I.E., Vecchietti, A., Kalvelagen, E., 2003. GAMS/DICOPT: A Discrete Continuous Optimization Package.

Gwamuri, J., Wittbrodt, B.T., Anzalone, N.C., Pearce, J.M., 2014. Reversing the trend of large scale and centralization in manufacturing: the case of distributed manufacturing of customizable 3-d-printable self-adjustable glasses. Challenges Sustain. 2, 30–40.

Haddadsisakht, A., Ryan, S.M., 2018. Closed-loop supply chain network design with multiple transportation modes under stochastic demand and uncertain carbon tax. Int. J. Prod. Econ. 195, 118–131. https://doi.org/10.1016/j.ijpe.2017.09.009.

Hakkens, D., 2019. Precious Plastic. http://preciousplastic.com/.

Hassanzadeh Amin, S., Wu, H., Karaphillis, G., 2018. A perspective on the reverse logistics of plastic pallets in Canada. J. Remanuf. 8, 153–174.

Hemmelmayr, V., Doerner, K.F., Hartl, R.F., Rath, S., 2013. A heuristic solution method for node routing based solid waste collection problems. J. Heurist. 19, 129–156.

Hemmelmayr, V., Smilowitz, K., de la Torre, L., 2017. A periodic location routing problem for collaborative recycling. IISE Trans. 49, 414–428.

IBM, 2019. Branch & Cut Or Dynamic Search? 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.

Juraschek, M., Cerdas, F., Posselt, G., Herrmann, C., 2017. Experiencing Closed loop manufacturing in a learning environment. Proc. Manuf. 9, 57–64.

Kannan, G., Noorul Haq, A., Devika, M., 2009. Analysis of closed loop supply chain using genetic algorithm and particle swarm optimisation. Int. J. Prod. Res. 47, 1175–1200.

Kannan, G., Sasikumar, P., Devika, K., 2010. A genetic algorithm approach for solving a closed loop supply chain model: a case of battery recycling. Appl. Math. Modell. 34, 655–670.

Kannan, D., Diabat, A., Alrefaei, M., Govindan, K., Yong, G., 2012. A carbon footprint based reverse logistics network design model. Resour. Conserv. Recycl. 67, 75–79.

Kietzmann, J., Pitt, L., Berthon, P., 2015. Disruptions, decisions, and destinations: enter the age of 3-d printing and additive manufacturing. Business Horizons 58, 209–215.

Kostakis, V., Papachristou, M., 2014. Commons-based peer production and digital fabrication: the case of a RepRap-based, Lego-built 3D printing-milling machine. Telemat. Informat. 31, 434–443.

Kostakis, V., Fountouklis, M., Drechsler, W., 2013. Peer production and desktop manufacturing: the case of the Helix_T Wind Turbine Project. Sci. Technol. Human Values 38, 773–800.

Kreiger, M., Pearce, J.M., 2013. Environmental impacts of distributed manufacturing from 3-D printing of polymer components and products. MRS Proc. 1492, 85–90.

Kreiger, M., Mulder, M., Glover, A., Pearce, J., 2014. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. J. Clean. Prod. 70, 90–96.

Laplume, A.O., Petersen, B., Pearce, J.M., 2016. Global value chains from a 3D printing perspective. J. Int. Business Stud. 1–15. https://doi.org/10.1057/jibs.2015.47.

Lyman, H., 2019. Lyman/Mulier Filament Extruder V5 by Hlyman – Thingiverse. http://www.thingiverse.com/thing:380987.

Ma, J., Chen, B., 2014. The complexity uncertain analysis about three differences old and new product pricing oligarch retailers closed-loop supply chain. Abstr. Appl. Anal. 2014, 1–11.

Mai, J., Zhang, L., Tao, F., Ren, L., 2016. Customized production based on distributed 3d printing services in cloud manufacturing. Int. J. Adv. Manuf. Technol. 84, 71–83.

Matt, D.T., Rauch, E., Dallasega, P., 2015. Trends towards distributed manufacturing systems and modern forms for their design. Proc. CIRP 33, 185–190.

McNaney, T., 2019. Filament Maker Filabot. http://www.filabot.com/.

Östlin, J., Sundin, E., Björkman, M., 2008. Importance of closed-loop supply chain relationships for product remanufacturing. Int. J. Prod. Econ. 115, 336–348.

Pati, R.K., Vrat, P., Kumar, P., 2010. Quantifying bullwhip effect in a closed loop supply chain. OPSEARCH 47, 231–253.

Pearce, J.M., 2017. emerging business models for open source hardware. J. Open Hardware 1. https://doi.org/10.5334/joh.4.

Peeters, B., Kiratli, N., Semeijn, J., 2019. A barrier analysis for distributed recycling of 3D printing waste: taking the maker movement perspective. J. Clean. Prod. 241, 118313. https://doi.org/10.1016/j.jclepro.2019.118313.

Petersen, E., Pearce, J., 2017. Emergence of home manufacturing in the developed world: return on investment for open-source 3-d printers. Technologies 5, 7.

PlasticsEurope, 2017. Plastics – THE FACTs 2017, An Analysis of European Plastics Production, Demand and Waste Data. https://www.plasticseurope.org/fr/resources/publications/plastics-facts-2017.

Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and chemical recycling of solid plastic waste. Waste Manag. 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044.

Rahim, F., Sepil, C., 2014. A location-routing problem in glass recycling. Ann. Oper. Res. 223, 329–353.

Realff, M.J., Ammons, J.C., Newton, D., 1999. Carpet recycling: determining the reverse production system design. Polymer – Plast. Technol. Eng. 38, 547–567.

Robine, F., Tomasini, R., 2018. Le “FabLab”, un incubateur de créativité et d’innovation. La lettre de la pédagogie 6. Technical Report. Académie de Nancy-Metz.

Sahebjamnia, N., Fathollahi-Fard, A.M., Hajiaghaei-Keshteli, M., 2018. Sustainable tire closed-loop supply chain network design: hybrid metaheuristic algorithms for large-scale networks. J. Clean. Prod. 196, 273–296. https://doi.org/10.1016/j.jclepro.2018.05.245.

Samanlioglu, F., 2013. A multi-objective mathematical model for the industrial hazardous waste location-routing problem. Eur. J. Oper. Res. 226, 332–340.

Sheriff, K.M.M., Nachiappan, S., Min, H., 2014. Combined location and routing problems for designing the quality-dependent and multi-product reverse logistics network. J. Oper. Res. Soc. 65, 873–887.

Sheriff, K.M.M., Subramanian, N., Rahman, S., Jayaram, J., 2017. Integrated optimization model and methodology for plastics recycling: Indian empirical evidence. J. Clean. Prod. 153, 707–717.

Singh, N., Hui, D., Singh, R., Ahuja, I., Feo, L., Fraternali, F., 2017. Recycling of plastic solid waste: a state of art review and future applications. Composites Part B: Eng. 115, 409–422. https://doi.org/10.1016/j.compositesb.2016.09.013.

Suzuki Moto France, 2018. Burgman 125. https://www.suzuki-moto.com/gamme-2018/burgman-125 (last checked on 01.12.18).

Suzuki Motor Corporation, 2018a. Small Car Loaded with Big Ideas. https://www.globalsuzuki.com/automobile/lineup/celerio/index.html (last checked on 01.12.18).

Suzuki Motor Corporation, 2018b. Burgman 200/125/ABS. https://www.globalsuzuki.com/motorcycle/products/uh125_200/ (last checked on 01.12.18).

Verboeket, V., Krikke, H., 2019. The disruptive impact of additive manufacturing on supply chains: a literature study, conceptual framework and research agenda. Comput. Ind. 111, 91–107. https://doi.org/10.1016/j.compind.2019.07.003.

Vidović, M., Ratković, B., Bjelić, N., Popović, D., 2016. A two-echelon location-routing model for designing recycling logistics networks with profit: MILP and heuristic approach. Expert Syst. Appl. 51, 34–48. https://doi.org/10.1016/j.eswa.2015.12.029.

Vink, E.T., Rábago, K.R., Glassner, D.A., Gruber, P.R., 2003. Applications of life cycle assessment to NatureWorks(tm) polylactide (PLA) production. Polym. Degrad. Stab. 80, 403–419.

Wittbrodt, B., Glover, A., Laureto, J., Anzalone, G., Oppliger, D., Irwin, J., Pearce, J., 2013. Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. Mechatronics 23, 713–726.

Woern, A.L., McCaslin, J.R., Pringle, A.M., Pearce, J.M., 2018. RepRapable Recyclebot: open source 3-D printable extruder for converting plastic to 3-D printing filament. HardwareX 4, e00026. https://doi.org/10.1016/j.ohx.2018.e00026.

Wongthatsanekorn, W., 2009. A goal programming approach for plastic recycling system in Thailand. World Acad. Sci. Eng. Technol. 37, 513–518.

Yousefi-Babadi, A., Tavakkoli-Moghaddam, R., Bozorgi-Amiri, A., Seifi, S., 2017. Designing a reliable multi-objective queuing model of a petrochemical supply chain network under uncertainty: a case study. Comput. Chem. Eng. 100, 177–197.

Yu, H., Solvang, W.D., 2016. An improved multi-objective programming with augmented ϵ-constraint method for hazardous waste location-routing problems. Int. J. Environ. Res. Public Health 13, 548.

Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., Perona, M., 2019. Supply chain implications of additive manufacturing: a holistic synopsis through a collection of case studies. Int. J. Adv. Manuf. Technol. 102, 3325–3340. https://doi.org/10.1007/s00170-019-03430-w.

Zhang, Y., Jedeck, S., Yang, L., Bai, L., 2019. Modeling and analysis of the on-demand spare parts supply using additive manufacturing. Rapid Prototyp. J. 25, 473–487. https://doi.org/10.1108/RPJ-01-2018-0027.

Zhao, J., Huang, L., 2015. An augmented ε-constraint algorithm to the hazardous waste location routing problem. ICTE 2015 – Proceedings of the 5th International Conference on Transportation Engineering 2847–2857.

Zhao, J., Ke, G.Y., 2017. Incorporating inventory risks in location-routing models for explosive waste management. Int. J. Prod. Econ. 193, 123–136.

Zhao, P., Rao, C., Gu, F., Sharmin, N., Fu, J., 2018. Close-looped recycling of polylactic acid used in 3D printing: an experimental investigation and life cycle assessment. J. Clean. Prod. 197, 1046–1055.

Zhong, S., Pearce, J.M., 2018. Tightening the loop on the circular economy: coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing. Resour. Conserv. Recycl. 128, 48–58.