**Life Cycle Assessment of Distributed Plastic Recycling via Additive Manufacturing.**

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**Abstract:** *Distributed recycling via additive manufacturing (DRAM) in a closed loop supply chain (CLSC) emphasizes a technical path to an emerging plastic recycling system. This technical system focuses on simplicity, minimization of environmental impact and high valorization of recycled waste. Recently major progresses are reported in various stages to validate the technical feasibility, environmental impact and economic viability of the DRAM system. However, little work has been done for the preparation and recovery stages, which involves logistics and the study of the whole recycling network. Thus, this work evaluates the environmental performance of implementing a DRAM system. Using life cycle analysis (LCA), an assessment of potential impacts of 1kg of recycled PLA was carried out considering the case of and university Fab Lab located in Nancy, France, where the DRAM strategy has been deployed. To evaluate this system, four impact categories were considered, climate change, potential eutrophication, resource depletion and ion radiation, showing, in 3 of them, environmentally favorable results due to the implementation of the DRAM system. This article provides an environmental overview of the benefits and disadvantages of developing a DRAM system in a specific context.*

***Keywords:*** *LCA, Recycling, Plastic, Distributed Manufacturing, Additive Manufacturing, Circular Economy*

# Introduction

Since the early 20th century, the invention of plastic, or synthetic organic polymers, changed the landscape of different industrial sectors. The production growth increased at compound annual growth rate of 8.4%, passing from from 2Mt in 1950 to 368Mt in 2019 (Geyer et al., 2017). This versatile material stands out as thanks to its easy processing and handling in shape, color, texture, thermal and barrier properties (making it ideal for food packaging) and its mechanical and chemical resistance (Andrady and Neal, 2009; Thompson et al., 2009 ). In consequence, 39.6% of the demand is used for packaging industry followed by construction and automotive industry with of 20.4%, 9.6% respectively of the production share (Plasctic Europe -, 2020). Unfortunately, the main problematic is associated with multiple environmental damages throughout its life cycle. Terrestrial, aquatic and atmospheric ecosystems are not exempt from the externalities of this innovation and represents a major issue (Kumar et al., 2021). Micro-, meso- and nano-plastics pollution contribute to detriement of ecosystem services such as ability to sequester carbon (Wang et al., 2022), soil productivity (Zhang et al., 2022) and eutrophication (Vuori and Ollikainen, 2022). Indeed, plastic pollution in the aquatic ecosystems such as standing waters can act as vector of toxic chemicals that affects the biogeochemical cycles. For example, every year 13 million tons of plastic end up in the oceans, which is equivalent to an entire garbage truck full of plastic being dumped into the sea every minute. A total of 150 million tons of plastic dumped into the sea to date (Pinto Da Costa et al., 2020). The presence of these solid plastic wastes has become a threat to marine ecosystems (Shi et al., 2022). Additionally, the transfer of plastic into the food chain is a clear danger to animal and, certainly, to humans as well. Therefore, the degrowth production of plastics is one of great importance in the long term.

The adequate use and disposal of plastics is a wicked problem characterized by high complexity and multifaceted feedback loops. A systemic view is needed of the entire plastics value chain including petrochemical companies (de Vargas Mores et al., 2018; Iles and Martin, 2013), converters (Paletta et al., 2019), brand owners or manufacturers (Gong et al., 2020; Ma et al., 2020), retailers and consumers (Confente et al., 2020; Filho et al., 2021; Friedrich, 2020), and recycling operators (Huysveld et al., 2019; Pazienza and De Lucia, 2020), as well as the influences of policy-makers in wider economic and societal changes (Paletta et al., 2019). The European Union (EU) intends to develop a circular economy (CE) based on a production and consumption model with key activities such as: “share”, “reduce”, “reuse”, “repair”, “renew” and “recycle” the existing materials and products as many times as possible, in order to create added value by extending the life cycle of products (European Commission 2018). Several critics have been raised given the thermodynamic constraints based on biodiversity and thermosdynamics arguments for a fully circular (Corvellec et al., 2021; Giampietro and Funtowicz, 2020). Nevertheless, as part of the European Green Pact presented on March 20, 2020, it is planned to establish an action plan involving the circular economy, mainly promoting the development of sustainable products, waste reduction and empowering citizens as a key player (European Commission, 2018). Considering the French context,a target was established that by 2025 all plastic waste should be recycled but currently recycling statistics in France reaches levels close only to 25%. Despite these ambitious objectives, plastics recycling has been historically an expensive process due to the inherent separate collection, transportation, processing and remanufacturing (Hopewell et al., 2009; Singh et al., 2017). The economies of scale have been leveraged to reduce these costs With centralized and global recycling chains (Kreiger et al., 2013; Kreiger and Pearce, 2013). Nevertheless, in order to carry out this recycling system, multiple steps need to be accomplished that integrate the sorting phase, long-distance transport, waste treatment and remanufacturing. The high costs of these processes and the low selling price (mainly due to the dependence of recycled plastic price on the petroleum and virgin prices) seldom generate benefits and often requires costly public subsidies (Hamilton et al., 2019). In addition, these centralized plastic manufacturing and recycling lines lead to soil, water and air pollution [Arena et al. (2003); ] (Arena et al., 2003; Reich, 2005). Added to the current problem into the plastic recycling network, we can highlight that generally supply chains are under increasing pressure from various stakeholders to make decisions from a sustainable perspective, that is to say, based on economic, environmental and social objectives (Hassini et al., 2012).

The additive manufacturing technology (also known as 3D printing) enables the potential of distributed manufacturing (DM) towards high value-added products (Kreiger et al., 2014). Nowadays, the accessibility of freely available designs has increased significantly, together with the development of open-source technologies and the supply of raw materials (virgin and recycled filaments) for 3D printing (Hunt et al., 2015). Distributed manufacturing is defined as the decentralization of production through the installation of multiple production factories with similar technology distributed geographically (Bonnín Roca et al., 2019). It is characterized by local production that thrives on the synergy of the emerging capabilities of digital manufacturing, information and communication technologies, and the peer-to-peer production approach (Kostakis et al., 2018; Kostakis, 2013; Pavlo et al., 2018). Indeed, DM offers the possibility to decentralize production structures, the flexibility to reflect local customer needs, lower logistics costs, shorter lead times and lower environmental impacts (Petersen and Pearce, 2017; Woern and Pearce, 2017). Based on the DM paradigm, a new possibility of plastic recycling supported by additive manufacturing, called distributed recycling by additive manufacturing (DRAM), has emerged in the literature (Cruz Sanchez et al., 2020; Hart et al., 2018). Promoted by the development of 3D printing in an open-source context, DRAM is proposed to provide recycled plastic feedstock to the different 3D printers in a DM context. This recycled plastic can be in the form of filament, and recent works are dealing with the validation of granular form (Alexandre et al., 2020; Justino Netto et al., 2021). The 3D printing feedstock is then obtained via plastic recycling at local scale using open-source machines, such as shredders and extruders (Zhong and Pearce, 2018).

The main feature of DRAM is the reduction of the impact in the collection phase, favoring shorter and simpler supply chains (Despeisse et al., 2017; Garmulewicz et al., 2018). Several works have focused on the validation of DRAM approach from the technical, economic and environmental perspective (Cruz Sanchez et al., 2020). Cruz Sanchez et al., (2020) conducted a systematic literature review about the level of development of the different DRAM stages from the technical perspective. Their results shown that significant progresses have been made in the stages of compounding, feedstock, printing and quality assessment. However, they also shown that on despite of that little work has been done for the preparation and recovery stages. In other, Santander et al., (2020) proposed an initial model to study the economic and environmental feasibility of DRAM from the logistic point of view. Their results have shown the feasibility of the system in economic terms and in CO2 emissions avoided implementing the system. From the environmental point of view, DRAM and DM approaches have been evaluated mainly using the Life Cycle Assessment (LCA) approach.

LCA is one of the most widely used environmental impact assessment methodologies. LCA corresponds to an ISO 14040 certified methodology, which has even been used for environmental regulations in different parts of the world. In the context of DM/DRAM-related research, LCA has been applied in different ways. For example, Kreiger & Pearce (2013) conducted a life cycle analysis (LCA), in terms of energy consumed and emissions involved, to compare centralized manufacturing and distributed manufacturing using RepRaps (3D printers) for the distributed production of goods. The results showed that the use of Poly Lactic Acid (PLA) in a distributed manufacturing context reduces energy demand and system emissions, which can be greatly diminished if a solar photovoltaic (PV) array is used. Later, Kreiger et al. (2014) explored the environmental benefit of distributed recycling using open-source extruders (RecycleBots), which have been used to obtain 3D printing filament from post-consumer goods. Focusing on High Density Poly-Ethylene (HDPE) as material, they performed an LCA of energy consumption and CO2 emissions to compare distributed recycling to standard centralized recycling. Their results showed that distributed recycling of HDPE uses less energy than the best-case scenario investigated for centralized recycling, and it can achieve savings of over 80%. Kerdlap et al. (2021), through a simulation approach, quantified the plastic life-cycle environmental impact of small-scale sorting and recycling systems compared to traditional large-scale centralized systems in Singapore, with the aim of determining under what conditions distributed recycling can be environmentally beneficial. Their results showed that the environmental impacts in terms of climate change, water depletion and terrestrial ecotoxicity were higher compared to the centralized systems. However, these results are mainly related to the means of transport considered for each system (commercial van for distributed recycling and large trucks for centralized recycling), since the use large trucks decrease the total impact.

In conclusion, even though different studies have been conducted aiming to validate the distributed recycling approach from the technical, economic, and environmental perspective, only the work of Kreiger et al. (2014) is focused on the environmental assessment of distributed recycling for 3D printing purposes. However, their research is limited to the consideration of energy and CO2 emissions as environmental indicators. Therefore, major effort needs to be made in order to evaluate, in a holistic way, the environmental impacts of the global DRAM value chain. Therefore, the contribution of this research lies in the evaluation of environmental impacts from the implementation of distributed recycling via additive manufacturing approach in a territory. Specifically, an environmental evaluation using life cycle assessment (LCA) is conducted comparing a distributed plastic recycling system to produce 3D filament with a traditional production system of virgin plastic filament for 3D printing. From this evaluation, the environmental impacts (positives or negatives) of implementing DRAM have been analyzed and discussed.

This article is structured as follows. Section 2 presents the system (case study) evaluated. Section 3 materials and methods, where life cycle analysis methodology is explained. Section 4 presents the life cycle analysis performed. Section 5 presents the discussion of results. Finally, Section 6 presents the main conclusions and recommendations for future works.

# Case study: The Lorraine Fab Living Lab

In order to achieve the objectives of this research, a case study with the following characteristics was selected:

1. Existence of a favourable context to implement a DRAM recycling system. A favourable context is defined as a considerable amount of plastic waste to be treated, as well as initiatives for the widespread use of 3D printing.
2. Existence of a space dedicated to the recycling of plastic for 3D printing.

Under these considerations, the selected context for this study was the Lorraine Fab living Lab[[1]](#footnote-2) (LF2L), an innovation space located in Nancy, France. This university laboratory has been selected mainly due to: (1) Innovation spaces such as Fablabs, Maker spaces, design factories among others have proven to be favorable environments for eco-innovations facilitating the implementation of circular economy strategies. Previous studies show that these collaborative environments enabling foster sustainable experimental learning, provide methodologies and tools for the co-creation of circular solutions, drive the transition toward sustainable smart cities, foster the creation of new sustainable business models, and facilitate knowledge exchange on circular solutions. (Kasmi et al, 2021), (2) the fact that since 2014, the LF2L is studying the possibility of recycling, in their installations, PLA for reuse in 3D printing. The pilot recycling process present in this center has been developed in the research work of Cruz Sanchez et al., (2017) and the possibility of implementing this recycling process in the region is being evaluated, and (3) an investment program has been launched by the Grand Est region to promote the use of 3D printers in the schools and high school of the region (Robine & Tomasini, 2018). The goal of this investment plan is that in the near future, all the schools and high school in the region will be equipped with this technology. This corresponds to the future scenario evaluated in the work of Santander et al., (2020). However, in our research work and in difference with Santander et al., (2020), a complete environmental evaluation of the scenario is carried out. As a consequence, this case study has been selected because their experimental experience of the DRAM strategy, the availability of technical and economic data and the already mentioned scientific publications that provide details on its local implementation. .

For this study, the context described above has been simplified in terms of geographical scale, and the following assumptions are considered.

* Only one type of plastic waste to be recycled is considered. Specifically, PLA has been considered. Mainly because PLA is one of the most used plastics in 3D printing (Bikas et al., 2016). As plastic waste sources, PLA waste from schools and high schools (who have 3D printers) has been considered. PLA has been selected as feedstock material due to the fact that (1) in Europe, PLA is considered as a "miscellaneous product" (EuRIC, 2020) owed to its Bioplastics category, and, at least in Europe, there is no defined recycling strategy for these types of plastics and they are usually sent to landfill or incineration, and (2) PLA is one of the most widely used plastics in 3D printing
* The recycling system modeled does not consider the sorting, separation and cleaning process because the collected material corresponds to a non-contaminated waste. For example, discarded 3D printing parts used for prototyping.
* From a geographical point of view, only schools and high schools in the Lorraine region (France) have been considered, and the route of recovery and delivery considered is obtained in the work of Santander et al., (2020).
* Each school and high school needs 1 kg of filament per month.
* The 3D printing activities carried out in these establishments have a specific purpose of making product prototypes and mock-ups, which allow to generate testing activities, design evaluations, functional evaluations, corrections. Therefore, after a short lifetime, 3D printing can be a source of significant amounts of plastic waste due to printed parts that do not possess the desired quality, unused raw materials, or products that have already fulfilled their life cycle (Alexandre et al., 2020).

*Figure SEQ Figure \\* ARABIC :Optimized route considered in the case study (Santander et al. 2020)*

# Material and methods

The chosen methodology is the life cycle assessment (LCA) because, in differences with other analytical methodologies with environmental focus, such as Material Flow Analysis (MFA), Substances Flow Analyses and Environmental Risk. it allows us to evaluate the environmental impacts of the system value chain to be modeled (Andersson et al., 2016).

The LCA represents a different tool and techniques created to determine in an effective and fast way the results to help with the management decision making in environmental terms and in the deepening of the sustainable development policy (Guinée, J. B., 2002).

Life Cycle Assessment (LCA) is a structured, comprehensive and internationally standardized method in accordance with ISO 14040 and 14044. It defines all the steps for its use: goal and scope definition, inventory analysis, impact assessment and interpretation (Pennington et al., 2004). LCA is a tool for quantitative evaluation of materials, energy flows and the potential impact of products, services or technologies (Dehghanian and Mansour, 2009). The analysis takes into account the entire life cycle of a product: from resource extraction, through production, use and recycling, to the disposal of the remaining waste (ILCD handbook, 2010). Several researchers have adopted LCA-based methodology to characterize environmental considerations for a range of pollutants (Graf, 2019).

Life cycle analysis has 4 main stages, the definition of objectives and approach (Stage 1), inventory analysis (Stage 2), impact assessment (Stage 3) and interpretation (Stage 4)

1. **Goal and Scope Definition:** This is the first stage and serves to orient the study bases. It defines the main objectives of the life cycle analysis, the target audience of this report, the functional unit that is the reference point from which the potential environmental impacts will be obtained, the limits of the system under study, the categories of environmental impacts to be evaluated and the hypotheses to be used in different stages of the LCA.
2. **Inventory Analysis**: The inventory is the stage in which the flows are quantified. it sets out the database used, the energy and material input, the calculations performed and how the system was modeled.
3. **Impact Assessment:** This stage presents the software used, the calculation methodology used to transform flows and characterize them into the impact categories evaluated. From this characterization, the impact profile of the system under study is obtained.
4. **Interpretation:** This is the conclusion of steps 2 and 3, the results obtained from the hypotheses used, the considerations and the functional study defined are presented. The phases of the life cycle that have the most impact is identified, and sensitivity analyses can be carried out to evaluate the behavior of the systems according to the variation of certain parameters. The inter-phase analysis stage is fundamental for decision making, as it identifies critical points and provides a basis for future improvements.

The LCA methodology is mostly used in an iterative way, allowing a better definition of the objectives to be achieved and the system to be analyzed.

In the following sections, a LCA is presented for DRAM using the Lorraine Fab Living Lab as case study.

# LCA application and results

## Goal and Scope Definition

The main objective of this life cycle analysis is to compare the potential impacts produced by a DRAM chain with the impacts produced by a traditional chain of virgin plastic filament for 3D printing.

## The functional unit

As mentioned above, this study will compare the environmental impact of two PLA 3D filament supply systems. As context of the study, the 3D filament will be supplied to all schools and high schools located in the city of Nancy, France. To compare two or more systems, it is necessary to define a functional unit that represents the service delivered by both systems. In this case the main service consists in the following one:

*" A monthly delivery of 1 kg of "standard" plastic filament (PLA) to each school and high school in Nancy during ten months of the year”.*

## System boundary

Figure 2 shows the two systems compared in this study and the processes integrated into the life cycle analysis. As can be observed, there are three different boundaries represented by colors green, blue and red. The first boundary (green color box) corresponds to the Biosphere, which represents everything related to nature, such as raw materials from natural resources, ecosystems, solar energy. The second boundary (dark blue color box) corresponds to the Technosphere limit, representing human activity (e.g. use of electricity, fuels, etc.) (e.g., electricity). Here, we can observe all the material flows that are considered for the life cycle analysis, the flows between processes or the flows that are part of the functional unit mentioned above. Finally, the boundary with light blue color represents the limit of the services and processes taken into consideration in this study. On the one hand, in the upper process flow, we can observe the processes considered in the system to produce filament from virgin plastic. The process starts with PLA production, PLA transportation, filament production and finish with product delivery. On the other hand, fig. 2 shows the recycling process enclosed in the orange box. The process starts with the collection of waste produced by schools and high schools, then the plastic recycling process, the production of filament and the delivery of filament are carried out.

Diagrama

Descripción generada automáticamente

Figure 3: System limits for life cycle analysis

## Selected impact categories

The objective of performing a life cycle analysis is to determine and evaluate the potential environmental impacts produced at different stages in the life cycle of a product, service, activity, or process. However, it is extremely difficult to identify, a priori, the categories of impacts in which the system under study is most detrimental (climate change, eutrophication, etc).

Two major domains were identified which are present in each of the scenarios evaluated. First, the production of plastics (in this case bioplastics) compared to the recycling of plastics. Second, the integration of these materials in additive manufacturing as raw material for the subsequent printing of products.

In order to define the more pertinent indicators to the DRAM approach, two literature reviews have been performed. In these literature reviews, studies of LCA evaluation applied to bioplastics (such as PLA) and additive manufacturing technology (3D printing) have been analyzed.

Considering the studies related to LCA applied to bioplastics evaluation, the literature review conducted by Bishop et al., (2021) evaluated the trends of the impact categories used across all the articles related to this topic. This review explored 44 LCA articles that compare the performance of selected bioplastics with the performance of petrochemical plastics. The results obtained of this literature review have shown that the most used impact category for bioplastics evaluation is climate change, followed by eutrophication potential variations, resource depletion, human toxicity photochemical oxidant formation, ozone depletion, ecotoxicity, human toxicity, particulate matter formation, energy consumption, land-use, and water consumption.

Regarding additive manufacturing technology, a literature review has been conducted, where articles related to the application of LCA in the context of additive manufacturing have been searched and analyzed. Then, the impact categories considered among the 4 articles found were analyzed. The results of the literature review have shown that the most evaluated impact category is the cumulative energy demand (CED) of the system (Cerdas et al., 2017; Kellens et al., 2017; Kreiger and Pearce, 2013; Quinlan et al., 2017). In addition, these authors have also considered climate change, potential eutrophication and human toxicity as the main impact categories included in the life cycle assessment.

Finally, after analyzing the two domains (LCA applied to bioplastics and LCA applied to additive manufacturing), it was decided to use the predominant impact categories in each of the industries, that is to say: climate change, potential eutrophication, and resource depletion (fossil and water).

## Assumptions and limitations

The realization of a full LCA involves the collection of information and data related to the different processes, flows and activities. Due to the difficulty of obtaining the necessary data, it is allowed to formulate hypotheses to partially fill the lack of data, on the condition that each of the hypotheses used and under which conditions they are formulated are made transparent.

The hypothesis formulation was mainly used to model the virgin plastic filament production system. The main hypotheses used are based on:

* Location polylactide acid production: This hypothesis indicates the location where the polylactic acid production process takes place.
* Location of filament manufacturer: Due to the uncertainty about filament production, two companies with different locations that are engaged in the production of plastic filaments have been modeled.
* Filament production machine: The machine PEEK 3d Printer Filament production Line[[2]](#footnote-3) has been considered, which corresponds to the machine used by the two filament manufacturers considered.
* Performance of the filament production machine: The machine selected to carry out the filament production process has a range of transformation from plastic pellets to filament. The range of the machine chosen for the evaluation has an output between 20 to 25 kg of filament per hour. This range directly affects the power consumption.
* Type of energy source used to conduct the recycling processes: Each country has its own technological mix to meet the electrical energy consumption, such as nuclear, solar, wind. These different sources of electricity are considered in the evaluation.
* Transportation of raw material and filament (virgin and recycled): The different options of means of transport used for raw material transportation and filament transportation are considered in the evaluation.

Based on these hypotheses, two scenarios were created to model the possible operation of the virgin plastic filament production system (see table 1). A third scenario represents the distributed recycling system for filament production, so the complete system is modeled with information obtained from the LF2L.

Table 1: Scenario definition

|  |  |  |
| --- | --- | --- |
| Production  System | Scenario | Description |
| Virgin  Filament | 1 | Scenario 1 begins with the production of PLA at the NatureWorks factory in Nebraska, USA. The PLA is transported by a combination of land and sea to bring the plastic from the United States to the filament manufacturing company called GEHR located in the city of Mannheim in Germany. In Germany, electricity is produced from wind power. From this location, the virgin filament is shipped directly to Nancy by light road transport. |
| 2 | Similarly, to Scenario 1, this scenario begins with the production of PLA at the NatureWorks factory in Nebraska, USA. The pellets of PLA are transported, by road, to the filament manufacturing company called 3D-Fuel, located in Fargo, USA. In the United States, electricity is produced from natural gas. From USA, the filament is shipped directly to Luxembourg using an air freight. Then, the filament is transported to Nancy using a lightweight vehicle. |
| Recycled Filament | 3 | This scenario starts with the collection of PLA 3D printing waste from the schools and high schools. The PLA waste is transported to the recycling point (Lorraine Fab Living Lab) using a light road transport. In this center, the size reduction process and the extrusion process necessary to produce the recycled filament are performed. The recycled filament is then delivered to the same schools and by the same transport, where the waste was collected. |

## Life cycle inventory analysis (LCIA)

## Data Source

To obtain the necessary data, different data sources were used to carry out the LCIA. On the one hand, for virgin PLA filament production, there are different life cycle analyses published by NatureWorks (Vink et al., 2003; Vink and Davies, 2015), where the results have been incorporated into the EcoInvent database. These articles helped to understand the PLA production process considering the production center in Nebraska (USA). For the virgin PLA filament manufacturing, NatureWorks proposes a catalog of customers who manufacture filament from PLA produced by the company, which facilitated the modeling of the supply chain to get to sell its product in the city of Nancy (France). On the other hand, for the plastic recycling process, the data concerning the input/output materials and the machines used in the recycling process were obtained directly from the Lorraine Fab Living Lab and from the thesis works conducted at ERPI laboratory related to DRAM (Cruz Sanchez et al., 2017; Santander et al., 2020). These data allowed modeling and understanding the recycling network, its main functions and its limitations considering the case study presented in section 3.

## Impact Assessment (LCIA)

## Calculation methodology

## Choice of the software

The software used to perform this life cycle analysis was OpenLCA 1.10.3. The main reason for its use was because it is an open-source software, so it’s easy for any user to get and use. This software allows to perform full life cycle analysis and carbon footprint analysis, allowing to install a wide variety of databases. For this case, the database used was the EcoInvent 3.5.

## Choice of calculation methodology and impact indicators

Analyzing the impact methodologies and considering the selected impact categories for this study (see section 4.1.3), ReCiPe (Global-Hierarchist version) has been chosen as impact calculation methodology. ReCiPe method (Goedkoop et al., 2009) has been chosen mainly because it is widely used in different areas of research (Dekker et al., 2020). In addition, ReCiPe is an LCIA method that is harmonised in terms of modelling principles and choices, offering results at both the midpoint and endpoint level (Goedkoop et al., 2009). In addition, it is used for various life cycle analyzes in the area of additive manufacturing with a hierarchical cultural perspective (Saade et al., 2020).

Finally, the set of impact categories chosen are presented in Table 2.

Table 2: Table of impact indicators and their unit of measure

|  |  |  |  |
| --- | --- | --- | --- |
| Impact Category | | Methodology | Unit |
| Climate Change | | ReCiPe (H) | Kg CO2 - Eq |
| Resources Depletion | Fossil Depletion | ReCiPe (H) | Kg OIL - Eq |
| Water Depletion | Kg P - Eq |
| Eutrophication Potential | Freshwater Eutrophication | ReCiPe (H) | Kg N - Eq |
| Marine Eutrophication | m3 |

## Impact studies

Table 3 presents the results of the comparison, showing for the virgin and recycled scenario, the amount of impact that is generated in each impact category evaluated. In addition, the percentage reduction comparing the recycling scenarios with the virgin scenario are presented. To construct this table, the best virgin scenario (least impactful) was considered for comparison. As result, it can be observed that the production of filament from recycled plastic has an important advantage in five of the six impact categories (climate change, fossil depletion, freshwater eutrophication, marine eutrophication, and water depletion), which corresponds to the categories considered essential for DRAM. The reduction in each of the categories corresponds to at least 97% compared to the impact produced by the virgin scenario. However, for Ion Radiation category, the recycling system has a greater impact than the virgin scenario (best scenario in this case). In the recycling scenario, the amount of ion radiation corresponds to approximately 2.8 times the emissions of the virgin scenario.

Table 3: Results of the impact categories per scenario and process

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | Impact of each process | | | | Total |
| Impact categories | Scenarios | PLA Production | Supply Transport | Filament production | Delivery |
| Climate change  (kg CO2-Eq) | Virgin Scenarios | 337.36 | [5.69- 18.19] | [1.94 – 32.60] | [54.43 – 785.24] | [411.92- 1160.88] |
| Recycled Scenario | - | 5.4523 | 2.289 | 4.957 | 12.699 (-97%) |
| Fossil Depletion  (kg oil-Eq) | Virgin Scenarios | 96.79 | [2.30 - 6.96] | [0.50 - 13.13] | [19.58-285.14] | [123.83 - 397.36] |
| Recycled Scenario | - | 1.961 | 0.615 | 1.783 | 4.359 (-97%) |
| Freshwater Eutrophication (kg P-Eq) | Virgin Scenario | 0.14 | [0.001- 0.002] | [0.001-0.003] | [0.011-0.024] | [0.159 0.168] |
| Recycled Scenario | - | 0.0011 | 0.0016 | 0.0010 | 0.004(-98%) |
| Ionizing Radiation  (kg U235-Eq) | Virgin Scenario | 26.51 | [0.45-1.49] | [0.12-0.15] | [4.46-52.78] | [32.61-79.86] |
| Recycled Scenario | - | 0.476 | 122.98 | 0.406 | 123.83 (+74%) |
| Marine Eutrophication (kg N-Eq) | Virgin Scenario | 0.89 | [0.004-0.041] | [0.003-0.009] | [0.09-1.30] | [1.02-2.20] |
| Recycled Scenario | - | 0.009 | 0.011 | 0.008 | 0.029 (-97%) |
| Water Depletion (m3) | Virgin Scenario | 37.3669 | [0.005-0.028] | [0.008-0.112] | [0.064-0.439] | [37.46-37.92] |
| Recycled Scenario | - | 0.006 | 0.546 | 0.006 | 0.56 (-99%) |

Figure 3 presents the impacts obtained for each studied scenario. As can be observed, distributed recycling system to produce 3D filament (recycling scenario or scenario 3) is the least impacting scenario taking into account the five categories considered pertinent to DRAM. The result shows that, in each impact category, the recycling scenario pollutes less than 5% compared to the two scenarios that integrate the production of virgin plastic. In other words, the recycling system to produce 3D filament manages to reduce emissions and impacts by at least 95%.

Regarding the other impact categories present in the ReCiPe methodology, it is necessary to emphasize that the recycling system has an important impact on the category that measures the radiation of ions equivalent to Uranium 235. Even as can be seen in the figure 3, scenario 3, which considers recycling, reaches a high radioactive emission compared to the scenarios considering the virgin filament. Scenario 1 represents approximately 25% of the impact produced by the recycling system, while scenario 2 (pessimistic scenario of virgin filament) represents approximately 60% of the impact produced by scenario 3.

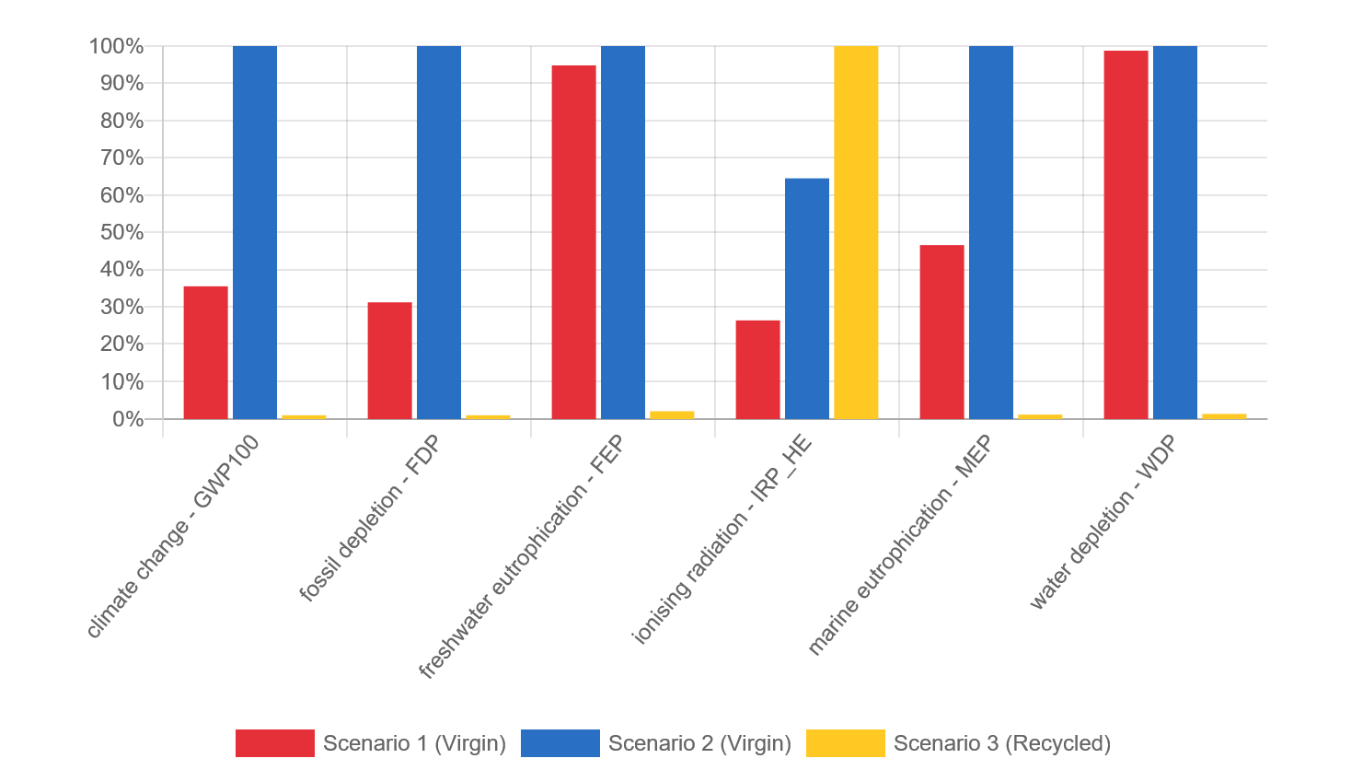


Figure 3: Comparison of the impact profile of each of the studied scenarios

## Interpretations and Recommendation

## Sensitivity analysis

In order to evaluate the response of each of the systems to context variations, a sensitivity analysis has been conducted. The sensitivity analysis consists of analyzing the results of the system against the variation of one of the parameters. This activity allows us to identify the the key contextual parameters that affect the results of the evaluation. These results can be favorable as well as the negative, being able to identify the effect called transfer of impacts . This effect consists in the fact that while in a specific impact category a reduction in the level of emissions is achieved through a change of parameters (technology, raw material, process, type of energy), at the same time there is one or multiple impacts in which an increase in emissions or impacts produced can be reflected. This effect (impact transfer) is fundamental when proposing improvements in products or services.

In this study, to have a better visualization of the transfer of impacts, the complete set of impacts evaluated by the ReCiPe (H) methodology have been taken into account.

## *Location of PLA production*

A recent project by Total Corbion has been proposed in Grandpuits (Seine-et-Marne). The purpose of this project is build a polylactic acid (PLA) production plant with a capacity of up to 100,000 tons per year, this first European plant is to be installed in France[[3]](#footnote-4). Considering this, a sensitivity analysis has been performed for this scenario. On this new scenario, the PLA production facility has been located in France at Total's Grandpuits facility.

Figure 4 shows the result of the change in the location of the PLA production plant (United States to France). To represent the sensitivity of the system, only the first scenario was considered because it has a logistics chain with less impact than scenario 2. Thus, it is interesting to see the changes with respect to this scenario. As can be observed, the result has a relatively small variation. Even though an improvement was obtained in some categories such as the particle formation, use of fossil raw materials or ozone depletion, the result is relatively small. The impact was not greatly reduced with respect to scenario number 1 because PLA production is the main source of impact in this scenario.

Gráfico, Gráfico de barras

Descripción generada automáticamenteIn conclusion, it was observed that there is a slight improvement in the environmental performance of the production system, but it is not sufficiently attractive with respect to the level of impact obtained in the recycling of plastic to produce filament. To obtain a significant improvement, it is necessary to continue optimizing the PLA production process, which is mainly given by technological advances that can be a great solution only if it manages to identify a slight transfer of impacts.

Figure 4: Sensitivity analysis respect to the displacement of the PLA production plant

#### Energy Source

The results presented in section 4.3.2 have shown that distributed plastic recycling to produce filament showed broad environmental advantages compared to production from virgin plastic. In almost all impact categories it had an impact of less than 5% of the impact caused by virgin filament production systems, except in the category related to the emission of radioactive particles. These emissions are closely related to the production of electricity from nuclear energy, which in France accounts for 68% of the total energy produced in the country. In 2020, the renewable energies represent 23.4% of the total electrical energy and increase strongly compared to 2019. The wind power production will increase by 17.3% and solar power production by 2.3%[[4]](#footnote-5). For this reason, it is key to see the response of the system and the possible transfer of impacts when using other forms of energy production, including mainly the use of clean energy (solar and wind).

Figure 5 presents the environmental performance of the recycling system using 3 different types of energy (nuclear, wind and solar).

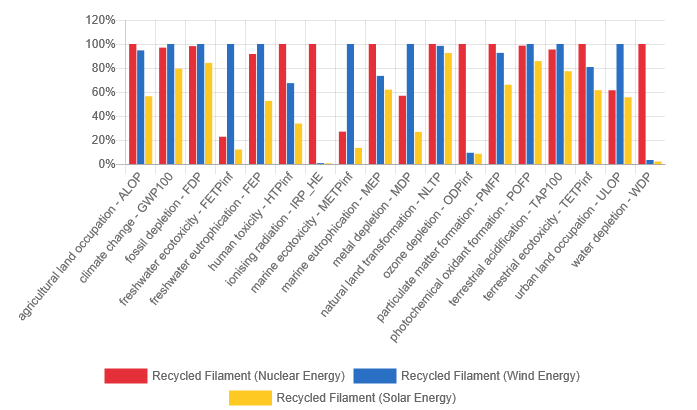


Figure 5: Sensitivity analysis respect to the type of energy used

As can be observed in Figure 5, the solar energy and the wind energy have different responses with respect to the use of nuclear energy. On the one hand, the solar energy (shown in yellow) considerably improves the environmental performance of the system, especially in the category of radioactive emissions, which is reduced by approximately 98%. Remembering that this category is the critical point in the comparison of the two filament production systems. In addition, a considerable improvement can be observed in the categories that consider ozone depletion and water use with reductions of more than 70%. No transfer of impacts is observed in any of the impacts evaluated. According to the impacts assessed, there is no transfer of impacts to other categories, being a more environmentally friendly option than the use of nuclear energy. On the other hand, the wind energy (shown in blue) also achieves significant reductions in the categories of impacts related to radioactive ion emissions, ozone depletion and water use. However, on this occasion, a transfer of significant impacts can be observed since, for example, the impact category measuring ecotoxicity in water (marine and fresh) increases its impact by 80% with respect to the use of nuclear energy, while the need for metals increases by 40%.

In conclusion, the use of solar energy may seem the best option among the energy sources evaluated. This type of energy presents a circumstantial improvement in the critical point of the use of nuclear energy without suffering a transfer of impacts. The use of wind energy does not have the same result, although it manages to reduce radioactive emissions, the use of this type of energy increases the toxicity presented in the water, which can directly affect different ecosystems as well as human health. To determine if this type of energy is suitable for the recycled filament production system, it is necessary to deepen the comparison of these two ways of producing electricity.

# Discussion

Distributed recycling via additive manufacturing (DRAM) has been considered by different authors as an alternative to increase the low plastic recycling rates in the world. Several researches have studied this recycling approach from a technical and logistics perspective (Cruz Sanchez et al., 2020; Santander et al., 2020). While other studies evaluated the environmental impact of this recycling approach considering only the recovery and recycling stages (M. A. Kreiger et al. 2014; Kerdlap et al. 2021). However, an assessment of the positive and negative environmental impacts of implementing this plastic recycling approach considering the whole chain (recovery, recycling and use) had not, until now, been conducted.

In this study, a life cycle assessment has been conducted in order to evaluate the environmental impact of implementing a DRAM system to produce recycled PLA filament, compared to a traditional virgin PLA filament production systems. In order to carry out this case study, a favourable context was defined in which a considerable amount of plastic is treated, 3D printing is widely used and there is a dedicated space for plastic recycling via 3D printing.

The result of the environmental assessment of this system have shown that the recycling system for filament production reduces the impacts produced by the best scenario of filament production from virgin plastic by at least 97%. The categories of impacts considered were greenhouse gas emissions (climate change), fossil material consumption (fossil depletion), overfeeding of aquatic ecosystems (potential eutrophication) and water consumption (water depletion). On the other hand, there is a transfer of significant impacts that is not considered in the "relevant" impacts of the production system, since, due to the use of nuclear energy to produce electricity in France, the emissions of radioactive ions increased by 280%, which means that the recycling process has a worse environmental performance in this category.

Despite the assumptions used, the scenarios related to virgin filament production have a major drawback, and that is that their most impactful or the most influential phase in multiple categories is the production of plastic. For this reason, the change in the location of the production plant only produces a minor environmental improvement. This means that, in order to improve the environmental performance of these systems, it is essential to develop new technologies and optimize the polylactide acid production processes.

For the recycling system, the sensitivity analysis performed has shown that the integration of solar energy can greatly reduce the impacts produced using nuclear energy, making it an extremely viable alternative for the recycling system. The wind energy, on the other hand, has a significant transfer of impact to the toxicity present in different types of water, which does not allow to define in the first instance whether it would be more convenient. In addition, the results showed that the DRAM approach is advantageous considering other energy sources (other than nuclear) that are used in other parts of the world.

The environmental assessment carried out in this study extends the results obtained by M. A. Kreiger et al. (2014) and Kerdlap et al. (2021), showing, based on LCA indicators, the environmental benefits carried out a distributed plastic recycling, and more specifically, implementing a DRAM system. In addition, the environmental benefits are independent of the energy source considered.

Therefore, this study indicates that, in environmental terms and under certain conditions, the implementation of DRAMs would have a positive impact on the territory of application and could have positive impacts in other contexts. Most notably, To the best of our knowledge, this is the first study to investigate the multidimensional environmental impact of implementing DRAM. The results show a huge potential in environmental terms of implementing DRAM and suggest the application of this recycling approach in different context, mainly due to the results obtained considering different energy sources.

However, this study is not exempt of limits to be considered in future works. For this reason, the following recommendations can be followed

* In order to reduce the complexity of the studied system, different hypothesis, such as, in the recycling system we considered an only one material collected in a clean state and fixed demand from schools. While, in the virgin production system the entire supply and production chain was formulated through hypotheses. Future research could conduct an environmental assessment incorporating these complexities.
* This study is limited to the comparison of DRAM with virgin filament production. It would be interesting to evaluate the environmental performance of a DRAM system with respect to other possible life-ends for PLA, such incineration, landfill or even a system where virgin material is incorporated into the recycling process. This is because the mixture of virgin and recycled material allows a considerable improvement in filament properties and printing quality.
* Finally, this evaluation was carried out by placing the DRAM system in a specific context of a developed country. It could be interesting to perform the same analysis in developing countries, which currently have major problems in the treatment of plastic waste (Ritchie et al., 2018).

# Conclusions

This work has demonstrated, using LCA methodology, the environmental benefits of a distributed closed loop supply chain network for plastic recycling using open-source 3D printing technologies in a specific context.

The results obtained by the application of the LCA methodology to the case study and its sensitivity analysis suggest the application of this recycling approach in different energy context (solar, wind and nuclear), acting in parallel to the existing centralized plastic recycling networks in order to increase the low plastic recycling rates.

As already mentioned in discussion section, it would be interesting for future works, reduce the assumptions used with respect to the production of virgin filament and to integrate the complexity existing today to carry out the plastic recycling process. Furthermore, assessing the impacts of this system in different territories allows to obtain a global vision on the performance of this system and which would be the most favorable context for its development.

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# Table of Figures

[1. Introduction 2](#_Toc100769580)

[2. Case study: The Lorraine Fab Living Lab 6](#_Toc100769581)

[3. Material and methods 7](#_Toc100769582)

[4. LCA application and results 8](#_Toc100769583)

[4.1. Goal and Scope Definition 8](#_Toc100769584)

[4.1.1. The functional unit 8](#_Toc100769585)

[4.1.2. System boundary 8](#_Toc100769586)

[4.1.3. Selected impact categories 9](#_Toc100769587)

[4.1.4. Assumptions and Limitations 10](#_Toc100769588)

[4.2. Life cycle inventory analysis (LCIA) 11](#_Toc100769589)

[4.2.1. Data Source 11](#_Toc100769590)

[4.3. Impact Assessment (LCIA) 12](#_Toc100769591)

[4.3.1. Calculation methodology 12](#_Toc100769592)

[4.3.1.1. Choice of the software 12](#_Toc100769593)

[4.3.1.2. Choice of calculation methodology and impact indicators 12](#_Toc100769594)

[4.3.2. Impact Studies 12](#_Toc100769595)

[4.4. Interpretations and Recommendation 14](#_Toc100769596)

[4.4.1. Sensitivity analysis 14](#_Toc100769597)

[*4.4.1.1.* *Location of PLA production* 15](#_Toc100769598)

[4.4.1.2. Energy Source 16](#_Toc100769599)

[5. Discussion 18](#_Toc100769600)

[6. Conclusions 19](#_Toc100769601)

[7. References 20](#_Toc100769602)

[Table of Figures 26](#_Toc100769603)

[Annex 1 Table of reference flows 28](#_Toc100769604)

[Scenario 1 Virgin filament System: 28](#_Toc100769605)

[Scenario 2 Virgin filament System: 28](#_Toc100769606)

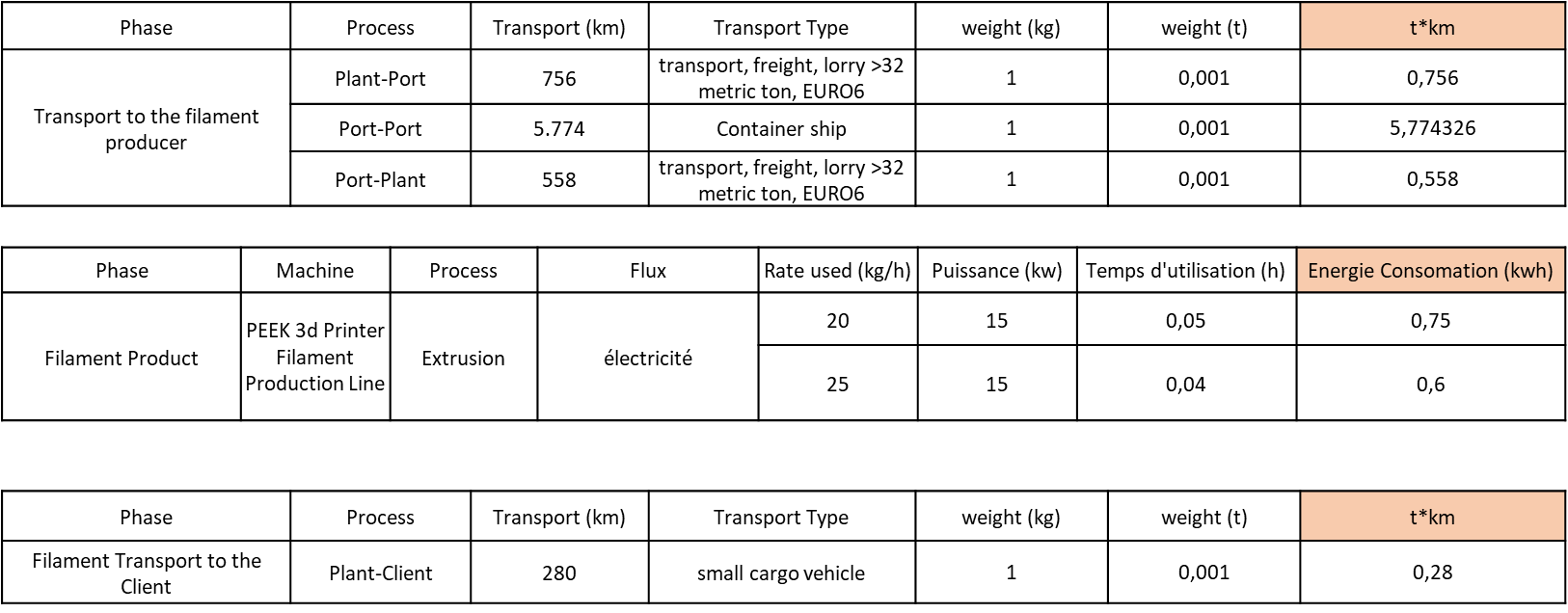
[Scenario 3 Recycled filament system: 29](#_Toc100769607)

[Representation of the 3 scenarios: 29](#_Toc100769608)

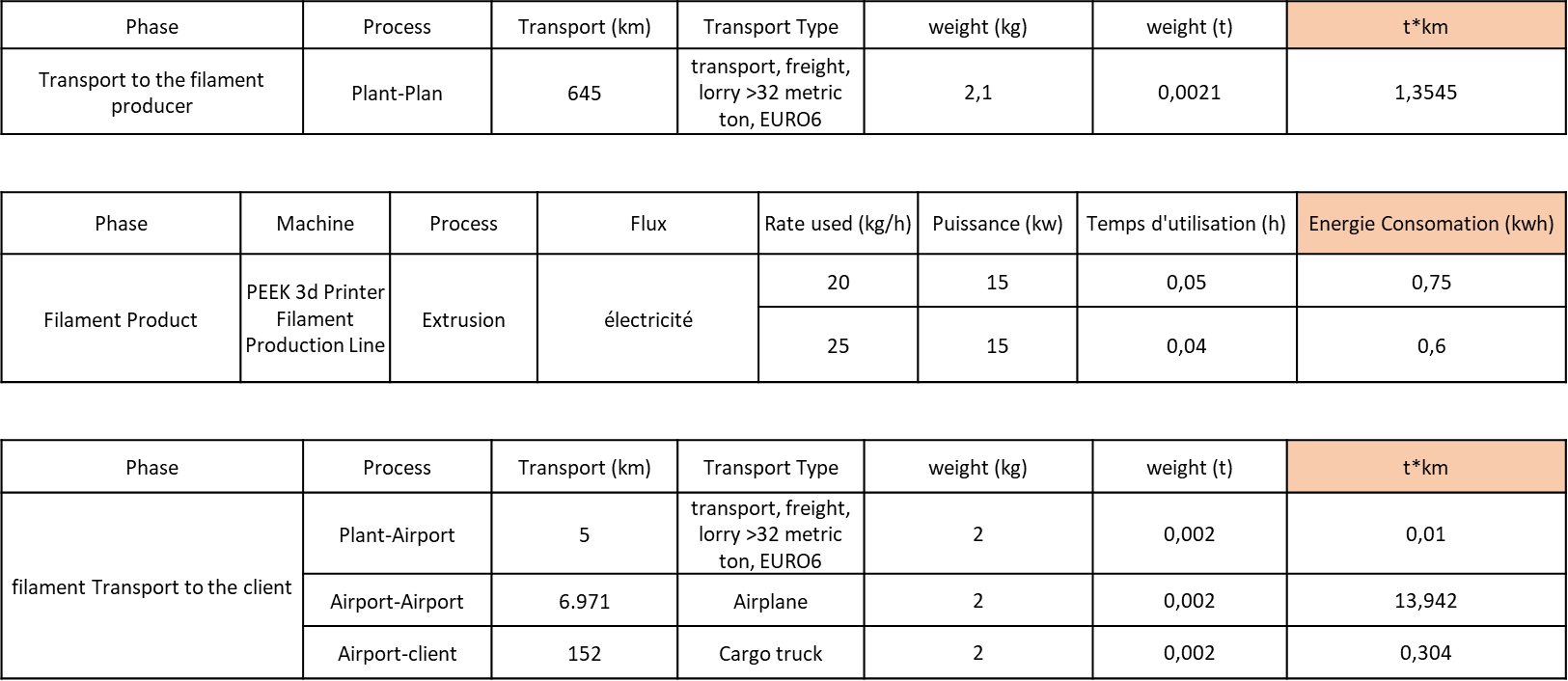
[Transport route for the recycling scenarios: 30](#_Toc100769609)

# Annex 1 Table of reference flows

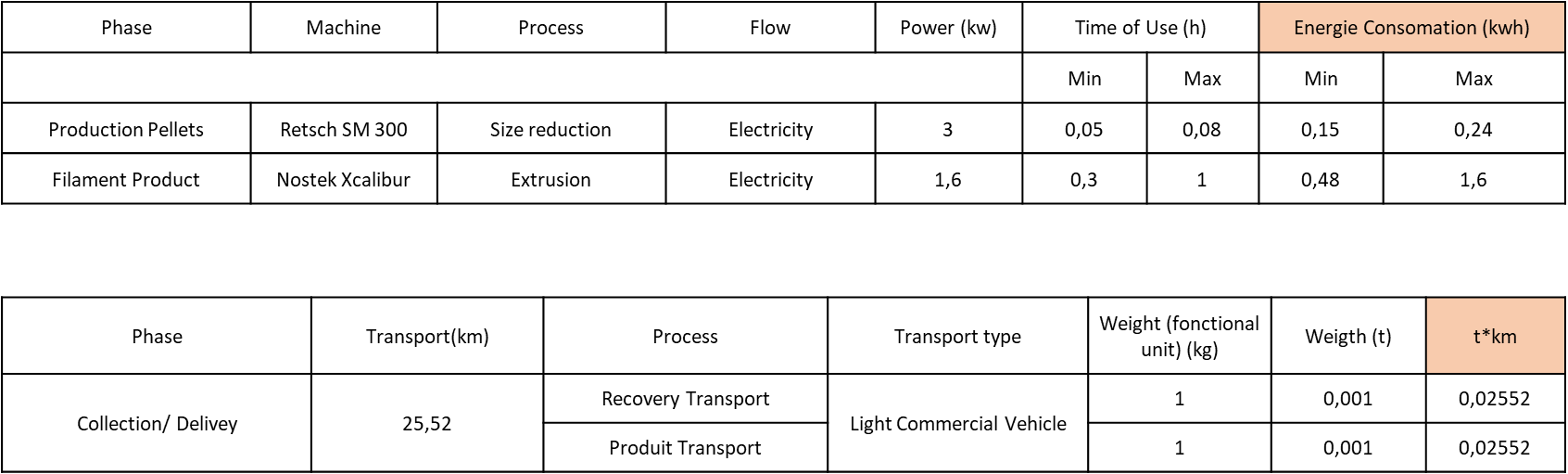
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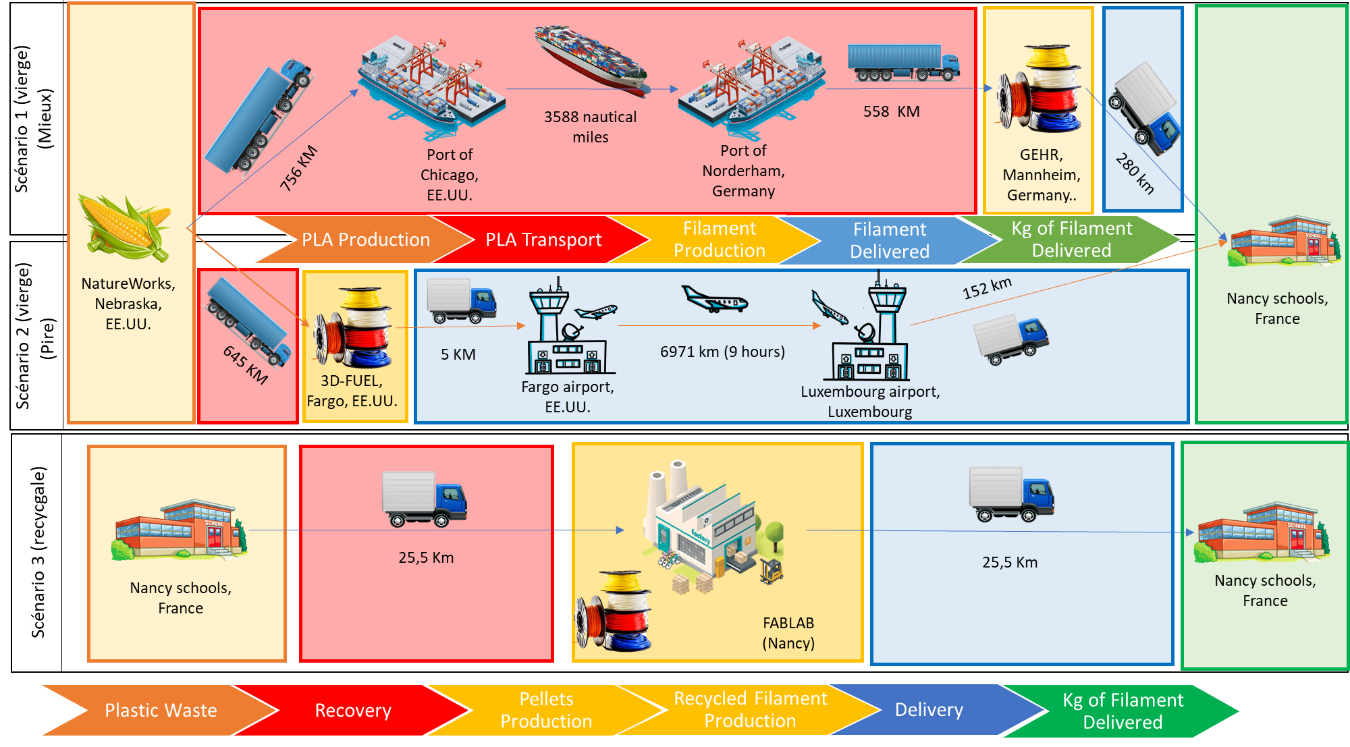
#### Scenario 2 Virgin filament System:



#### Scenario 3 Recycled filament system:



#### Representation of the 3 scenarios:



#### Transport route for the recycling scenarios:

Une image contenant carte

Description générée automatiquement

1. <https://lf2l.fr/projects/green-fablab/> [↑](#footnote-ref-2)
2. More information about the machine in [www.accextrusion.com/product/peek-3d-printer-filament-production-line.html](http://www.accextrusion.com/product/peek-3d-printer-filament-production-line.html) [↑](#footnote-ref-3)
3. <https://www.usinenouvelle.com/article/bientot-du-pla-made-in-france.N1216857> [↑](#footnote-ref-4)
4. <https://bilan-electrique-2020.rte-france.com/production-production-totale/> [↑](#footnote-ref-5)