Journal of Cleaner Production 382 (2023) 135287

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# Digital twin of end-of-life process-chains for a circular economy adapted product design – A case study on PET bottles

Jeff Mangers *, Mahdi Amne Elahi, Peter Plapper

*Faculty of Science, Technology and Medicine, University of Luxembourg, Luxembourg*

ARTICLE INFO

*Keywords:*
Circular economy
Product lifecycle
Process chain
Value stream mapping
Decision-support tool

ABSTRACT

The concept of Circular Economy (CE) is gaining increasing attention as an indispensable renewal of linear economy without neglecting sustainable development goals. Closing resource loops and keeping resources in the system at the highest level of use for as long as possible are cited as the main goals of CE. However, due to missing information exchange, the lack of consistency between the existing end-of-life (EOL) infrastructure and the respective product designs hinders a successful circularity of resources. This research presents a method to collect, process, and apply EOL process data to provide the beginning-of-life (BOL) with important EOL-knowledge through a CE-adapted product design assessment. EOL-data is collected using a Circular Value Stream Mapping (C-VSM), EOL-information is processed using a digital state flow representation, and EOL-knowledge is applied by providing a decision-support tool for product designers in the context of a PET bottle case study in Luxembourg. The goal is to anticipate a circular flow of resources by reflectively aligning product design with the relevant EOL infrastructure. In contrast to the linear economy, the developed method makes it possible to consider not only the requirements of users but also the actual end users, the EOL process chains, when designing products.

## 1. Introduction

In today's linear economy, resources are taken from the planet to create products that are subsequently thrown away as waste. In 2019, the EU's average packaging waste per inhabitant was 177 kg, with 19% plastic packaging, of which only 40% has been recycled back into plastics, including down-cycling (Eurostat, 2021). The circular economy (CE) is mentioned as a promising concept to reduce resource use by reintroducing them into the system, thereby solving the problem of waste generation. Consequently, CE has awakened curiosity among scholars (Merli et al., 2018), researchers, professionals, and politicians (Kalmykova et al., 2018), because it is considered an operationalization for companies to implement the concept of sustainable development (Azevedo et al., 2017). However, several barriers and hurdles (e.g., technical, cultural, market, and regulatory barriers) (Grafström and Aasma, 2021) prevent a successful transition. This is mainly because most sectors focus on making a linear system circular rather than applying CE principles holistically (Gusmerotti et al., 2019), such as by aligning products with existing EOL conditions, which requires better information exchange between EOL and BOL (Mangers et al., 2021).

An adapted product design is grouped under design for everything (DfX) or, in this case, design for circularity (Moreno et al., 2016), which aims to enable improved information sharing between product designers, service managers, and the EOL (Sassanelli et al., 2020). The literature mentions that potential EOL process issues need to be considered during the product design phase (Lin, 2018), meaning that the choices and decisions made during the product design phase have a significant influence and impact on the circularity performance (Saidani and Harrison, 2021). For (van Schaik and Reuter, 2013), one fundamental design for recycling (DfR) rule is that within Computer-Aided Design (CAD), process and system design tools must be linked to recycling system process simulation tools to realize technology-based, realistic, and economic viable DfR. However, the current lack of expertise in CE product design translates into limited attention to EOL design, which according to (Grafström and Aasma, 2021) is due to a lack of data on waste streams and impacts. Based on this shortcoming (Acerbi et al., 2022), conducted a study of the data needed to support CE. The first example of circular design decision support is given by (Pozo Arcos

* Corresponding author. Kirchberg Campus: 6, rue Coudenhove-Kalergi, L-1359, Luxembourg.
*E-mail address:* jeff.mangers@uni.lu (J. Mangers).
*URL*: http://www.uni.lu (J. Mangers).

https://doi.org/10.1016/j.jclepro.2022.135287
Received 18 May 2022; Received in revised form 6 November 2022; Accepted 21 November 2022
Available online 22 November 2022

et al., 2018), who explore existing design strategies, guidelines, and product features that enable functional recovery operations like repair, refurbishing, or remanufacturing. The second is given by (Kuo et al., 2019), who proposed a decision-making model to assess and implement sustainable product-service systems (PSSs), considered one of the leading circular business models nowadays. An industrial case study of PSS in the food and bakery machinery sector is given by (Sassanelli et al., 2021), which promotes knowledge management within the design process by developing and integrating a service feature. The shortcoming of these studies, as well as other studies (Favi et al., 2017; Toxopeus et al., 2018) is that they are mostly at a theoretical level and do not address practical applications nor consider the actual EOL process specification of a given region.

These aspects are reinforced by reports from public institutions (Circular Economy Initiative Deutschland 2021; ECR, 2021), which call for the recyclability of packaging to be considered as early as the design phase and cite a lack of transparency and insufficient compatibility throughout the value chain as causes of system losses. A look at the numbers reinforces these claims. The EU Packaging and Packaging Waste Directive 2018/852 specifies that by 2030, 55% of plastic packaging and 70% of packaging waste are to be recycled (European Union, 2018). However, in 2019, only about 40% of plastic packaging waste was converted back into plastics, including downcycling (Eurostat, 2021). For PET packaging, around 49% were collected and sorted for recycling (61% bottles and 21% trays) across Europe. Due to additional losses during the recycling process and diversion of material flows for other purposes, only 17% rPET was reintroduced into the PET bottle production stream (EUNOMIA, 2022), thus revealing a considerable potential for improvement.

As mentioned above, researchers and public institutions are asking for ways to improve product designs in terms of circularity. However, the offer of possible solutions is minimal, especially regarding application-oriented solutions. This problem is currently being addressed primarily by offering design guidelines (ECR, 2021; RecyClass, 2022; Eco Design, 2022; EPBP, 2022) that provide general information about sorting and recycling practices and suggest ways to improve packaging design. These guidelines are a proficient reference point, but they are general and based on the fact that existing EOL processes are up to date. They do not consider the conditions in a specific region, i.e., local differences. This makes the design guidelines complex to apply and incomplete about actual conditions on the ground.

This research aims to virtually replicate EOL process chains to assess product designs' conformity with local conditions. An essential part is the independent analysis of EOL process chains, which forms the basis for the later product design evaluation. In the following, the steps necessary for this are described in more detail, i.e., how the required data is collected, then further processed into information, and finally made available as knowledge, using the example of a PET bottle use case in Luxembourg. This allows information collected during the product life cycle to be used for product design (Preut et al., 2021) and is in line with Luxembourg's CE priorities, which identify resource-efficient design as a top priority (Ministère de l'Énergie et de l'Aménagement du territoire, Ministère de l'Environnement, and L'Economie, 2021).

The rest of the publication is structured as follows: Section 2 gives an overview of the current state of the art, Section 3 describes the methodology used, Section 4 outlines the results, Section 5 the discussion, and Section 5 gives a conclusion.

## 2. Relevant work

Based on Ulrich's applied research methodology (see Section 3), it is necessary to review the theoretical procedures required to describe the problem and analysis. Thus, the topic of CE is illuminated regarding Industry 4.0 (I4.0) before the Value Stream Mapping (VSM) topic is examined in more detail regarding CE and data collection. To conclude, the research gaps in this research are highlighted, and the main terminology is defined.

### 2.1. Circular economy & industry 4.0 – background

CE and I4.0 are the two main industrial paradigms that have driven academia and industry in recent years (Suárez-Eiroa et al., 2019), with several systematic literature reviews available (Agrawal et al., 2022; Chari et al., 2022). Most definitions of I4.0 consider advanced digital technologies as the primary driver of it, including technologies such as big data, analytics, simulation, the Internet of things, etc. The integration of these technologies within an industrial context can enable purposes related to CE paradigms, for example, Product Lifecycle Management (PLM) (Rosa et al., 2020), by providing precise information such as location, availability, and flow of components, thus helping in decision-making (Ghoreishi and Happonen, 2020). The combination of both is called 'circular I4.0' (Rosa et al., 2020) and refers to the importance of data gathering and information exchange to enable a successful paradigm change towards CE. One much-discussed possibility is using digital twins (DTs) to support data modeling and exchange (Preut et al., 2021; Wang and Wang, 2019). DTs are used throughout the PLM from design through manufacturing, delivery, and use to EOL (Lo et al., 2021), for example, in the form of a durable design tool (Ghoreishi and Happonen, 2020). Thus, digital technologies can help close the material loop by focusing on the EOL and establishing a link toward production (Pagoropoulos et al., 2017).

The assessment and analysis of CE within value chains are mainly done using different indicators (Saidani et al., 2019). However, there is also the possibility to refer to the 9R framework (Kirchherr et al., 2017) or the hierarchy of waste/value, which sets a priority order for the best overall environmental option in waste legislation and policy (European Parliament and Council of the European Union, 2008).

### 2.2. Value Stream Mapping (VSM)

The basic VSM concept was developed by (Rother and Shook, 1999), and further details regarding defined calculation procedures were provided by (Erlach, 2013). ISO standardized VSM symbols, parameters, and calculation procedures in 2020 to ensure a common understanding (Mangers et al., 2020). The value stream management method is an effective tool for collecting, evaluating, and continuously improving product and information flows and is divided into three main phases: VS analysis, VS design, and VS plan (ISO 22468 2020). Typically, VSM visualizes material and information flows within companies and focuses on time, which has been extended by further applications over time. Recently, a significant focus has been on combining VSM with sustainability (Edtmayr et al., 2016; Faulkner and Badurdeen, 2014; Garza-Reyes et al., 2018). Most sustainability VSMs include additional indicators and assessments line (e.g., energy and water consumption) and aim to use more sustainable processes to produce sustainable products. Concerning CE aspects (Edtmayr et al., 2016) included three re-utilization cycles for waste material into VSM as well as several sustainability indicators (Galvão et al. 2020). focused on connecting value streams within circular business models and their ecosystems, whereas (Hedlund et al., 2020) investigated how companies and industrial systems and networks might use VSM as a tool to enhance sustainability and accelerate change towards an eco-friendly, circular economy. The most recent publication about VSM and CE is from (Hernandez et al., 2021), which presents an adaption of the VSM through the integration of a set of indicators related to the concepts of circularity and longevity.

The last aspect explored in the current literature is the applicability of VSM to analyze and improve information flows (Meudt et al., 2017). developed VSM4.0 to analyze and visualize the current state of value streams in terms of material, especially for information flows, digitalization, and I4.0. The novelty of this method is to capture and address various information logistical wastes to individual processes. To do so, rows for information storage media and usage are added beneath the individual processes and connected through a line indicating the direction of the information flow. The background is to generate and transfer data before processing and storing the data and finally utilizing the data to enable decision-making. Their colleagues later added the aspect of VS design, so how to design an efficient and integrated information flow (Hartmann and Metternich, 2020). Similar studies have been done by (Mangers et al., 2020; Busert and Fay, 2019; Lewin et al., 2017), which analyzed the information handling within companies concerning I4.0.

### *2.3. Research gap*

Based on the aforementioned relevant work and discussions with industry experts, the research gap is divided into three areas:

1) There is a lack of a holistic view of value streams to CE requirements, especially regarding the connection between EOL and BOL. Thus, interrelationships of overarching process chains are lost at company boundaries.
2) There is a lack of application of digital solutions in practice about CE to link EOL and BOL and illustrate their interaction and interdependence. This is also related to the lack of specific information about the EOL process, which makes developing products for improved EOL compliance difficult and complex.
3) Currently, it is impossible to evaluate product designs for their actual region-specific CE compliance. This gap encompasses the two previously mentioned areas and serves as an overarching research gap.

In summary, there is a lack of methods to collect, process, and apply EOL process data during the early life conception of products, resulting in a lack of knowledge exchange between EOL and BOL.

### *2.4. Summary of main terms*

The ability to link EOL process information to BOL product design follows the product and process modeling approach based on characteristics and properties from Computer-Aided x (CAx) (Vajna et al., 2018), which is extended by process capabilities.

(1) Product Characteristics are the main aspects of the product design which significantly impact a product's EOL outcome. In the PET bottle use case, they are divided into four categories, main material (e.g., PET bottle), closure system (e.g., HDPE cap), decoration (e.g., paper label), and location. These parameters can be directly influenced by product development.
(2) Process Properties are different parameters that determine the conditions of the processes by measuring, for example, the used material quantity, the consumed energy, or the processing time. They are in line with the traditional VSM and are indirectly influenced by product development.
(3) Process Capabilities are the abilities of a process that determine the criteria used to decide about the outflow of a resource flow. They are the decision criteria (e.g., PET/not-PET, label size smaller than 50%, etc.) of a process that dictates the material flow and needs to be considered during product development.

A further distinction is that according to the PLM phase in which a company operates. The following distinction is made:

BOL companies are active in the manufacturing of products and are, therefore, before the actual use phase of the product.

EOL companies are active in reprocessing products and are, therefore, after the actual use phase of the product, i.e., collection & sorting, and recycling.

## 3. Methodology

The findings presented below result from a detailed case study of more than 10 individual company analyses within the same supply chain, aiming to identify cross-company problems and better understand the individual interrelationships. The PET bottle in Luxembourg was well suited for this, as almost all SC partners are located nearby, it is a partially functioning CE chain, and it consists of a material that has attracted a lot of attention in recent years. The analysis started with a water-filer, from which all up (PET bottle, preform, closure, and label manufacturers) and downstream companies (sorting and recycling facilities) were considered. The actual analysis consisted of a VSM analysis of the individual companies, which included a one to two-day visit with the recording of process information. To avoid any influences, all companies involved in the SC were considered, and the data collected were simplified and anonymized for this publication not to share any critical information.

The research methodology from (Ulrich, 1984) for applied science was followed, divided into 7 sub-steps to follow a clear structure. It starts with capturing and typifying practice-relevant problems (step 1) before these are reviewed within the available literature (steps 2 & 3). The next step is to acquire and investigate the relevant application context within the industry (step 4), followed by a derivation of general methods or models (step 5). The last two steps consist of testing the developed methods or models in the application context (step 6) in combination with a practice consultation (step 7). Applied science takes problems from practice as a starting point for research, examines the context of the application, and finally ends up back in practice. This approach makes it possible to investigate the problems dealt with, which mostly have their origins in practice, in a scientifically sound and application-oriented way. Thus, problems identified in practice were reinforced by statements from the literature review to develop a common solution. In general, the interdisciplinary approach is practice-oriented, open, and integrative.

Fig. 1 summarizes the research methodology used. It starts with the two correlated subjects of consideration: the respective EOL processes and a CE product design. This means that a product may or may not be adapted in terms of its circularity depending on local process conditions, which need to be known beforehand (compared with different plug connections for electronic devices based on the country of sale). Thus, in the analysis phase, three successive steps are carried out, based on ISO 22468 and in line with the knowledge pyramid (Rowley, 2007), which deals with how to get from data to information to knowledge to be able to make decisions consciously. In the synthesis, the region-specific process capabilities are linked to product characteristics using algorithms, resulting in a data-based decision-support tool for product designers used to validate the developed method.

## 4. Results

The research gaps mentioned in section 2.3 are solved by the three-step method described below, which specifies how EOL-specific process information can be collected, processed, and applied. The method is intended to be generally applicable and is presented here using the PET bottle as an example. The individual method steps aim to create a digital representation of the EOL infrastructure based on the data collected and to carry out a CE assessment for product designs. To ensure that fewer resources are lost in the future and products can be designed according to CE criteria, a more precise knowledge of EOL processes is of utmost importance. The methodological steps presented below significantly contribute to this by providing specific guidelines and examples of how such an understanding of EOL can be gained and used.

The remainder of this section is organized as follows. First, the most important terms are briefly explained, essential for a better understanding of the idea behind the method steps. Then, the three method steps are described in more detail, one by one, and each is illustrated

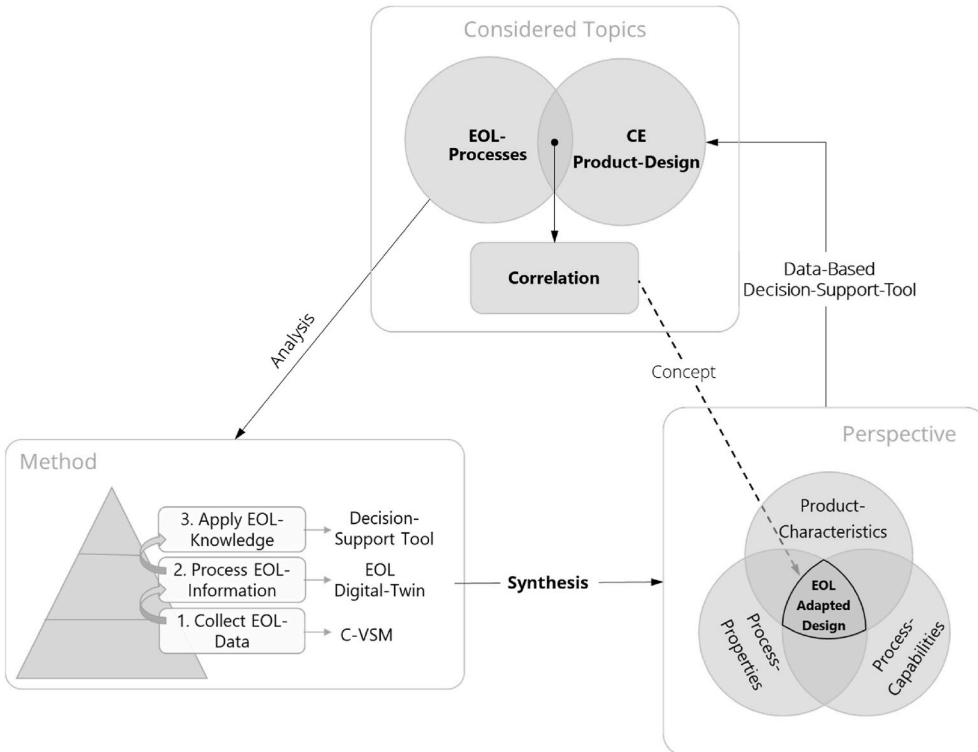


**Fig. 1.** Used research methodology and method modules.

with application examples for the PET bottle. Each step is then discussed regarding its explanation.

### *4.1. VS-Analysis – collecting EOL-data*

The first step, collecting specific EOL process data, is performed at two levels, micro-level (company) and macro-level (complete SC), using C-VSM.

#### *4.1.1. Micro-level*

Since the micro-level deals with company-level analysis, the first component is the process properties used to quantify process consumption. They are divided according to the defined CE goals (Mangers et al., 2021): closing and slowing of resource loops, minimization of waste, and sustainability. The indicators are divided into dependent (circularity) and independent (sustainability) indicators to meet the previously defined objectives, as visualized in Fig. 2. The dependent indicators directly influence the material flow, whereas the independent indicators influence sustainability. The selected indicators do not represent the totality of possibilities but the ones that seem most relevant for this case study and can thus be adapted according to the requirements.

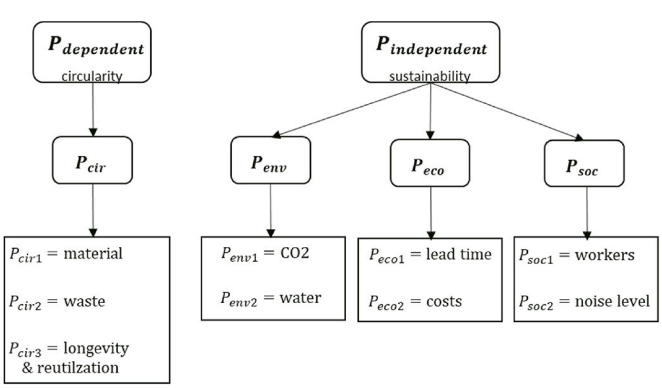


**Fig. 2.** Sub-division of C-VSM indicators.

There are few adjustments for companies operating in BOL compared to a traditional sustainability VSM. The main differences are new process properties, and a stronger focus on the differentiation of resource flows. An example of a C-VSM from a water-filling company can be found in (Mangers et al., 2021).

For companies active at the EOL, the C-VSM includes further novelties, mainly about the information flow. The idea behind the new information gathering is taken from (Meudt et al., 2017) and adapted to the needs of CE. Meaning the inclusion of the three previously mentioned reference points (product characteristics, process properties, and process capabilities), aiming to link a product design (product characteristics) towards its respective effects during the EOL reprocessing (process capabilities). The idea behind this is to determine for each process its specific capabilities and to what degree the strategy can work correctly and at what point this is no longer possible, and link those towards the respective product design categories. The general structure is illustrated using the example of a sorting machine with a Near-InfraRed (NIR) (left, sorting plant) and a swim/sink process (right, recycling plant) within Fig. 3.

Each process box contains a certain number of indicators which are regrouped under 'Process Properties' and indicate the number of operators, number of machines, the SCrap Rate (SCR), eNeRGy consumption (NRG), Water Consumption (WC), the Processing Time (PT), and the Noise level (N). Above, the process capabilities are listed in vertical form, together with the respective flow direction. In the example shown here, the process differentiates between not PET (flow direction 1) and PET (flow direction 2). In contrast, a too-large label size (flow direction 3), the same as the color carbon-black (flow direction 3), hinders the machine from detecting the correct material. A label size larger than 50% hinders the machine from detecting the material properties behind the label. In contrast, carbon black has the property that it does not reflect the NIR-rays, which prevents the material from being detected.

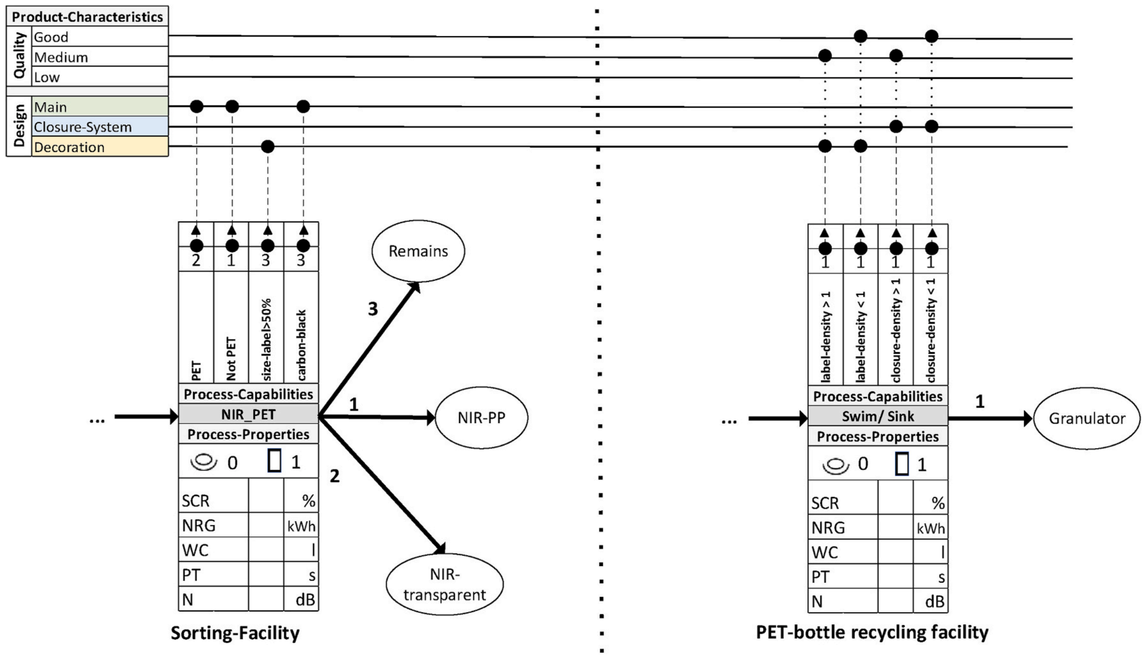


**Fig. 3.** The general structure of the information flow.

The process capabilities are connected to the product characteristics through a vertical line with a dot at the respective intersection. The product characteristics are divided into the three already previously discussed categories, the same as they indicate the respective quality (good, medium, and low). In the shown example, the not PET, PET, and carbon-black capability of the process is linked to the main body part of the product, whereas the label size capability is linked to the decoration category. Since this is a pure sorting process, there is no influence on the recyclate quality but only on the flow direction. The quality aspect plays a role in the recycling process (see Fig. 3, right side), whereby the

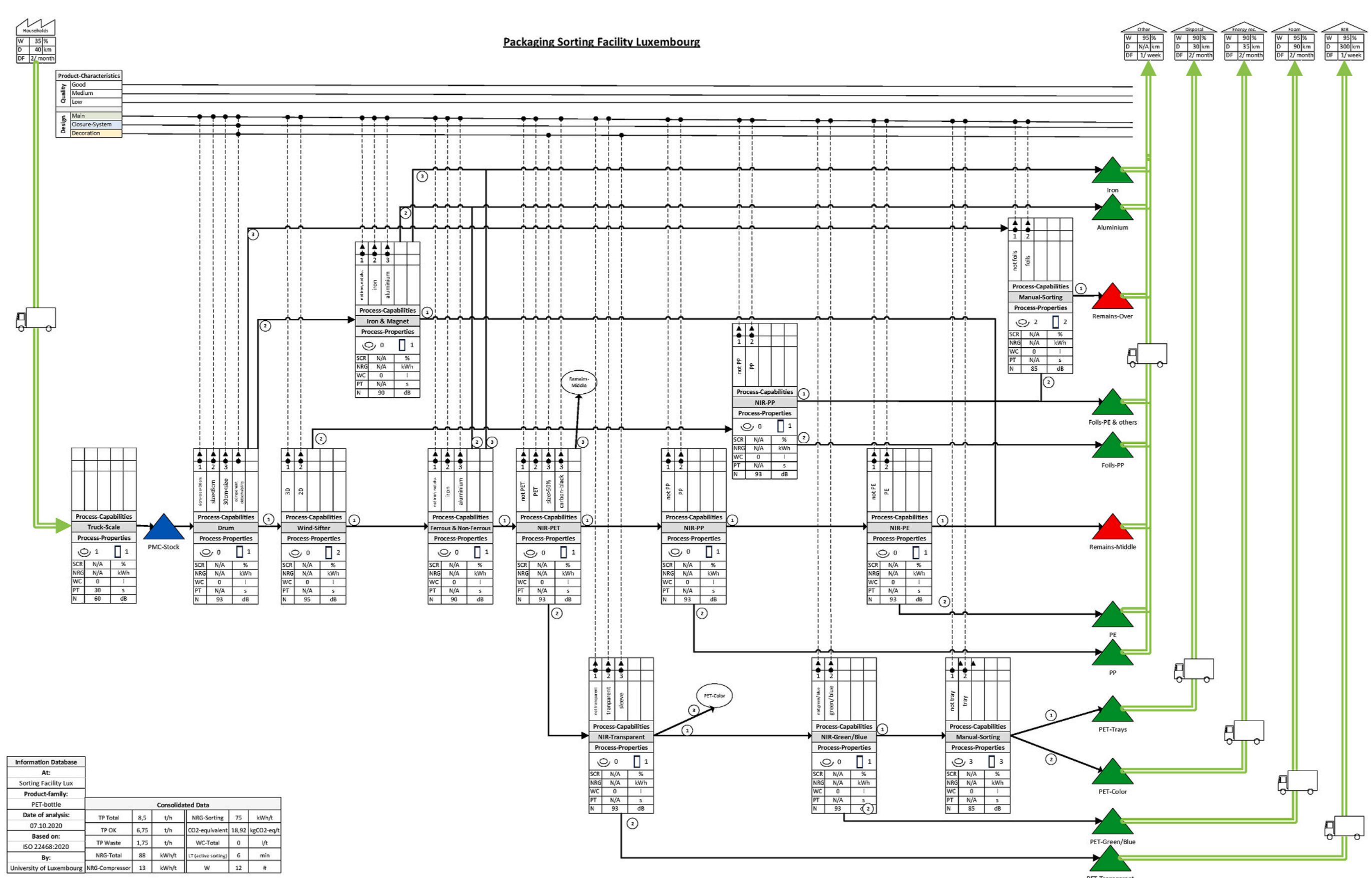


**Fig. 4.** C-VSM of a packaging sorting facility.

characteristics no longer influence the product flow but mainly on the quality of the subsequent recyclate. Thus, a label or closure density below 1 g/cm$^3$ results in good PET quality, whereas a density above 1 g/cm$^3$ prevents separation of the label or closure and the PET (density: 1,38 g/cm$^3$) body material and thus deteriorates the recyclate quality. In the following, the idea behind this is explained and illustrated using the example of a packaging sorting plant (Fig. 4).

Sorting facilities differ from most production facilities because they have one input (blue bag, which contains other packaging waste) and several output streams representing the sorted fractions. After weighing the received quantity, different processes are followed, separating the received content more precisely. The first process is a drum, which separates the initial fraction according to its size, followed by a wind shifter which sorts according to the packaging form (2D foils or 3D containers). Thereinafter, a ferrous and non-ferrous attraction, the same as several material-specific NIRs are following, whereas the last process is mostly a manual sorting. As already mentioned, most processes depend on the main packing part and do not influence the quality of the recyclate but only on the resource flow direction. The C-VSM of the local sorting facility in Luxembourg illustrates the influence that product design can have on the proper functionality of EOL processes. The respective process capabilities and product characteristics provide an in-depth overview and insight into the EOL infrastructure and guide on which product designs can be processed locally.

### 4.1.2. Macro-level

The macro-level VSM is a compilation of the respective micro-level VSMs and differs significantly from traditional VSMs. The depiction of a circular flow of resources and the CE value is achieved by referring to the swim lane alternative and including the previously mentioned 9R framework (Kirchherr et al., 2017). Each level of the swim lane represents a specific CE value, whereas the lowest level defines the overall value of the SC. The 9R framework is included as a vertical value hill on the right side of the diagram ranging from R0 (highest) to R9 (lowest). Since the three highest Rs (refuse, rethink, and reduce) are only reachable through an adapted design, they are depicted collectively on the design level. The second value is the actual use phase, during which the product has its highest value. All other Rs are subsequently included except for the last one, namely 'disposal', which has no CE value and should be avoided. The information flow indicates which SC-partner is responsible for providing information (EOL) and which one is responsible for receiving the needed information (BOL). Fig. 5 illustrates the complete SC.

This new representation helps depict and view SCs holistically and allows to better understand the interrelationships within an SC and trace the connections and dependencies among the individual companies. The data summary of the individual SC partners makes it easy to see which company has the most significant potential for improvement (e.g., goal: improve CO2 emissions, it makes sense to start with the company responsible for the highest CO2 emissions). In contrast to most studies, the method presented is not about classical production and manufacturing but about the EOL processes that have so far operated more in the background and allows getting further insights into the effects a product design can have on its respective EOL scenario.

This was the last part of the VS Analysis. The following section deals with the VS Design, explaining how the collected data gets processed.

## 4.2. VS design – processing EOL-information

The VS design elaborates on transforming the different C-VSMs into

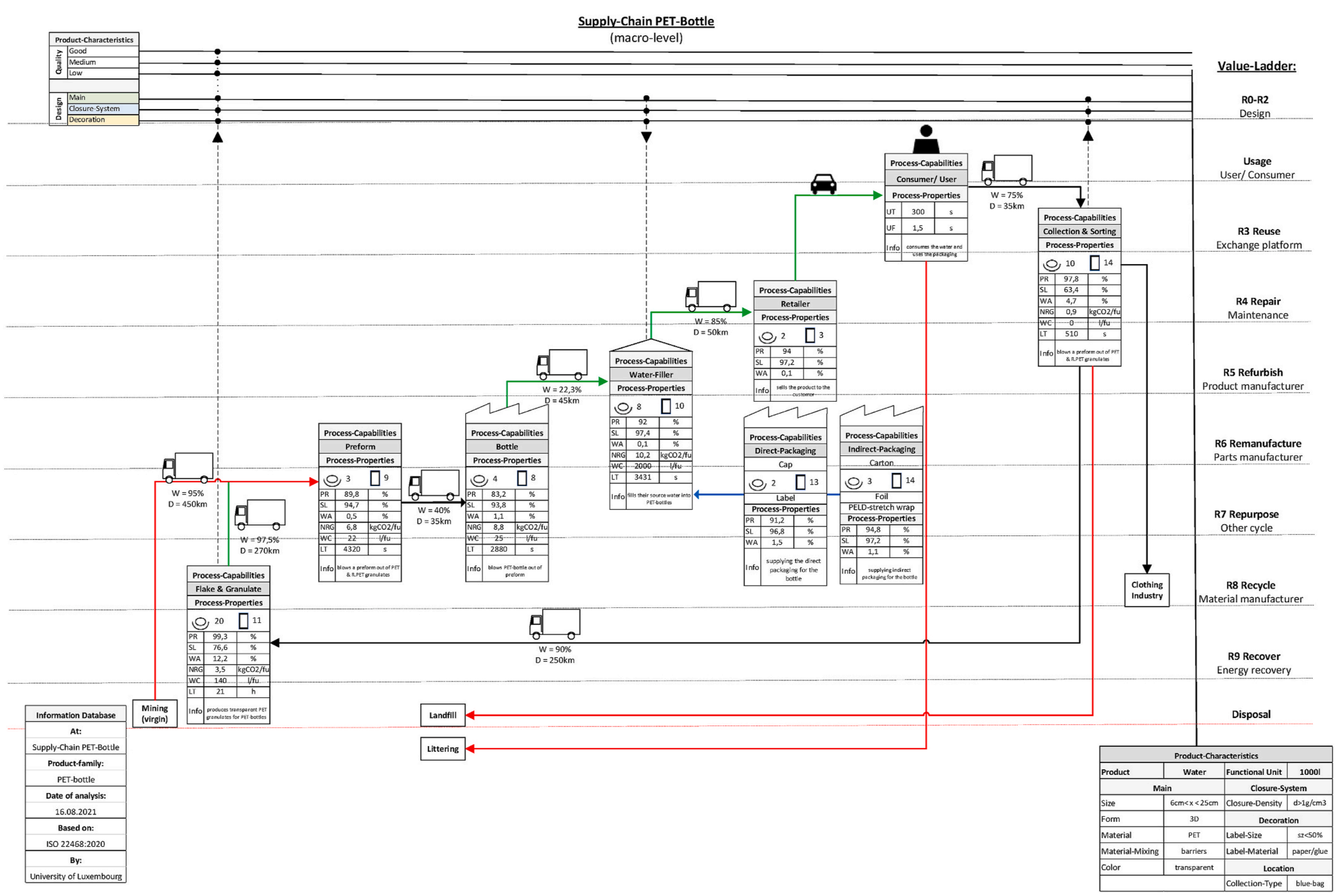


**Fig. 5.** C-VSM of the PET bottle supply chain.

state flows. According to the automata theory, the collected process capabilities are transferred into decision criteria (node decisions) within the state flows (Vossen and Witt, 2016). This is necessary to transfer the collected EOL-information into a digital twin with the same process criteria as the existing infrastructure. It makes it possible to simulate different scenarios with the developed model later.

The state flows of the various resource flows can now be represented directly in MATLAB and thus used for the later targeted simulations. This approach allows using the information on a holistic level, which in this case concerns all packaging products of the Luxembourg market (e.g., PET bottles as well as PP yogurt cups or LD-PE film). Fig. 6 shows an example of a simplified state flow of the before-mentioned packaging waste sorting facility in Luxembourg and, therefore, can be seen as its digital twin.

The rectangles represent the different processes (different states), and the circles visualize the start or end state of the sorting system, all connected by arrows. Above the arrows, the sorting criteria of the individual processes are listed. For example, these are the different size ranges for the first process and for the second process, whether the product is 3-dimensional (e.g., bottle or cup) or 2-dimensional (e.g., foil). Referring to Fig. 6, if the entered material value corresponds to PET, the fourth state will be NIR-transparent, if the material value does not correspond to PET, the fourth state will be NIR-PP. It is essential to mention that this state sequence represents the different processes of a specific sorting plant in Luxembourg and cannot be used as a reference for possible sorting processes in other countries, which may be completely different.

To visualize and simulate a given input parameter over the entire given SC, it is necessary to include all given information from the EOL processes in the digital representation. In this way, different super-states are created, which summarize the different processes of a company and connect the different companies (macro-level). These super-states are composed of the individual processes of a particular company (micro-level). For example, the recycling plant focuses on recording the information, i.e., the criteria that influence the quality of the recyclate (see Fig. 3, right). This virtual representation or digital twin of the existing EOL process chains is the prerequisite for the subsequent simulation, which is explained in more detail in the next section.

The second step makes it possible to use the collected EOL information locally by a single party and make the information available to a larger audience. In this way, any party wishing to become active in a particular market can easily use the information already available. It is essential to mention that information sharing is secure regarding data security, as the digital twin acts as a black box for external users. Users can use the digital twins without insight into the exact company processes.

### 4.3. VS-plan – applying EOL-knowledge

The last step clarifies how the information gained can be translated and transferred into knowledge easily applied by the BOL responsible. It answers how the EOL-information can be transferred to the BOL, thus linking EOL and BOL.

A platform with selectable product characteristics must be implemented and connected to the digital EOL process chain. The product characteristics are specific product design criteria chosen by the product designer and are mainly influenced by marketing and economic aspects. With new rules and laws put in place, e.g., by 2025, 50% of plastic packaging needs to be recycled (European Union, 2018), it becomes increasingly crucial for packaging producers to design their products in a way that they can and will be recycled. Thus, they need to adapt their product characteristics to meet the respective capabilities of the available EOL processes. The product characteristics are divided into four main sub-groups, which are based on (ECR, 2021):

(1) Main component (e.g., material, form, size, etc.)

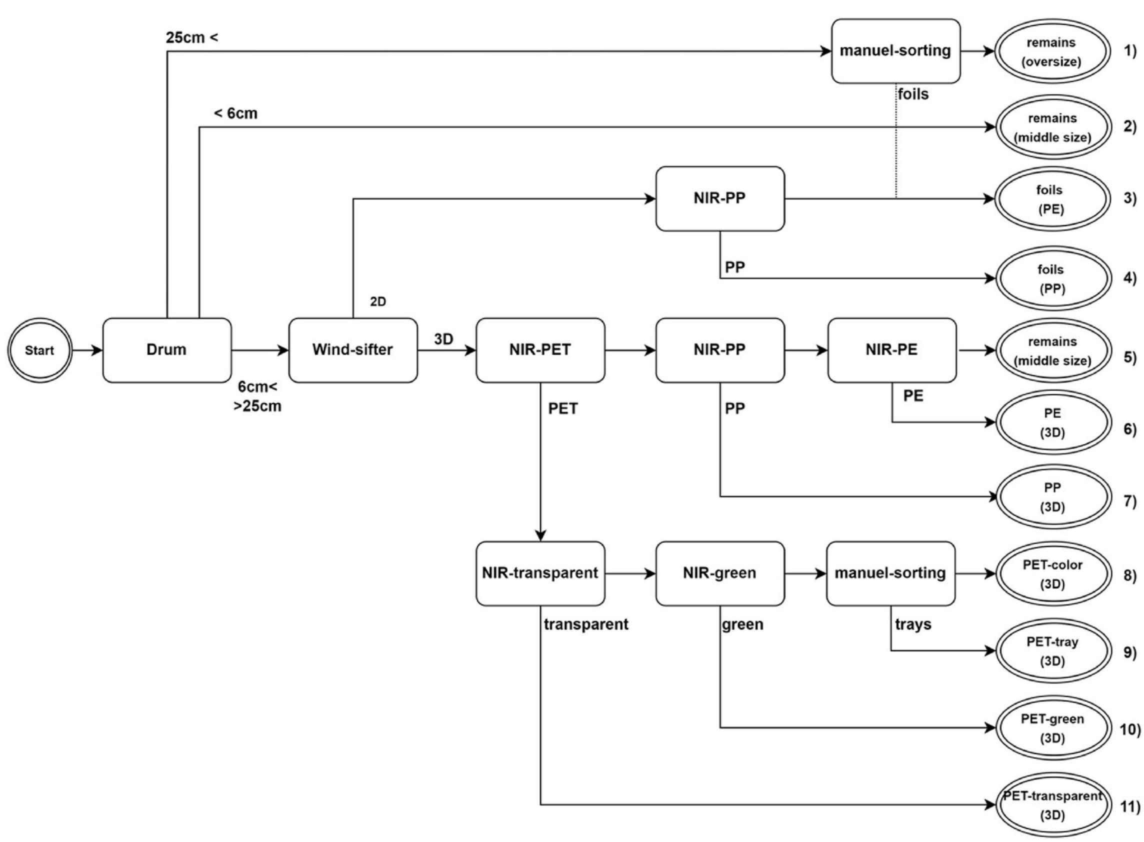


**Fig. 6.** Simplified state-flow of a sorting facility in Luxembourg.

(2) Closure system (e.g., cap material)
(3) Decoration & other components (e.g., label size, label material, etc.)
(4) Location (to intercept local differences)

The first three categories combine the available guidelines and the collected EOL process information (e.g., PVC significantly influences the recycling process). The fourth category represents regional and national differences within the EOL infrastructure. In Luxembourg, there is the possibility to hand in the packaging in a collection bag (blue bag), which is later sorted in the shown sorting plant or to hand in the packaging independently in so-called resource centers. This is an essential innovation of this model in contrast to the current guidelines. Because by linking it to the digital representation of EOL process chains, it is possible to evaluate a product design in terms of the EOL processes that are actually in place.

For this research, the platform was created as a Graphical User Interface (GUI) in MATLAB, shown in Fig. 7. On the left side, the selection of product characteristics (input) of a packaging design is presented. The results, the same as the potential improvement potentials, are shown on the right side of the GUI. The top part (blue) shows the fraction into which the respective design is sorted within the sorting facility, the same as after the recycling, and gives a qualitative indication of the quality of the recycled material. This is the assessment of the design about its CE adaption. The below part (green) indicates improvement potentials for each of the respective product-characteristics categories.

With the required exchange platform, it is possible for BOL responsible to quickly simulate and assess the effects of their designs on the EOL without any prior knowledge, which is comparable to a finite element simulation. Instead of simulating how various loading scenarios will stress a component, it simulates what will happen to the product based on its design at its EOL, better known as CAR. Implementing a customized design is a compromise or trade-off between the technical specification, marketing, and lessons learned about the EOL possibilities of a product. It is worth noting that the goal of this work is only to provide the right people with the needed information and not to be in opposition to the marketing department. If the necessary information is available and public institutions demand higher recycling rates, chances are that something will change.

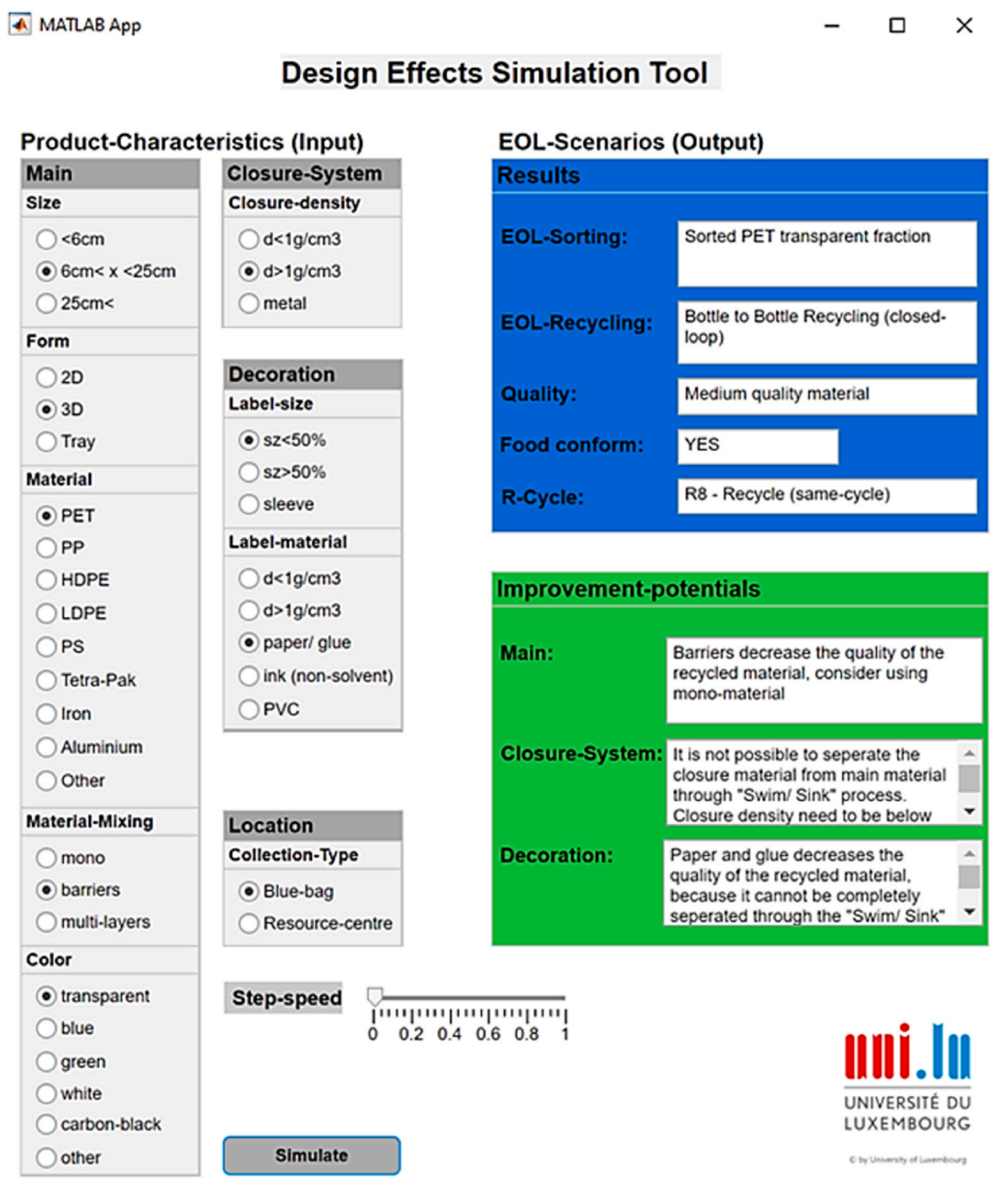


**Fig. 7.** GUI of the simulation tool.

## 5. Discussion

There are two main possibilities to improve material uptake. Either the EOL processes themselves can be improved, or the corresponding design can be adapted. It is necessary to enhance and harmonize EOL processes over time but alone is insufficient, as it will always be one step behind. Regarding effort and outcome, starting at the very beginning and adapting the product design to the EOL conditions is more efficient than the other way around. This is easier to apply, cheaper, and better accepted, which was shown in this study. This way, the information collected during the C-VSM analysis is used locally to improve a particular process and, more holistically, to communicate the information gathered to the people in charge. If the respective process chain changes in the future, this can easily be adjusted, thus keeping the "digital twin" up to date.

The presented method, with its decision-support tool, is the first step towards a CAR that is oriented towards the actual existing conditions and thus makes a decisive contribution to the current state of knowledge. This enables practical and management implications, as the presented results can be directly translated into actions. The assessment of CE applicability will play an increasingly important role in the future paradigm shift. In addition to the results of the EOL, the quantitative data collected, such as electricity or water consumption, could be displayed. Thus, the presented results fit well into the current spirit of the time. Considering the CE targets outlined in the introduction (55% of plastic packaging to be recycled by 2030) and the current numbers (around 50% losses of PET packaging in the collection and sorting in 2020), there is still much to be done in this regard soon. Better coordination and exchange between BOL and EOL will become increasingly important in the future (Mangers et al., 2021; Ghoreishi and Happonen, 2020), with the need to link the circularity performance of a given product to the performance of the company developing it (Saidani and Harrison, 2021).

## 6. Conclusion

This paper addresses a combination of CE and I4.0 and aims to combine EOL and BOL effectively. The main limitation is that the developed method has been applied to only one case study, requiring further use cases for a more general applicability check, mainly concerning higher Rs. Second, the method only applies to products for which a supply chain and, more importantly, recovery processes already exist, but not to products for which the supply chain has yet to be established. This is verified by a decision support tool in a PET bottle use case.

The method itself can be regrouped and summarized through the following three steps that address three research gaps in this paper:

1) Collecting data: using C-VSM to collect specific EOL process data

Since the EOL situation is currently more of a black box, the insights collected and presented will help better understand cross-company difficulties and consider them specific, local data. The first step thus closes research gap 1 and can serve as a reference point for the standardization and harmonization of regional or EU-wide EOL processes.

2) Processing information: converting the collected data into a digital twin

The transfer of the collected data into a digital representation of the EOL processes helps to consider the region- or country-specific process capabilities, the so-called boundary conditions, in the subsequent product design phase. In contrast to design guidelines, these results enable a better understanding of the background and reasons why a chosen design is good or bad, increase transparency and take region-specific differences into account.

3) Applying knowledge: providing a decision-support tool

Evaluating the product characteristics compared to the actual EOL processes makes it easy for the product designer to improve his design in terms of CE criteria without much effort. Thus, research gap 3 was also considered and supported that the high losses in collection and sorting and lower losses in recycling can be reduced without much effort. Moreover, these efforts will only be beneficial if the demand for recycled materials in BOL increases, which can happen through customer pressure or policy mandates.

To conclude, it is essential to mention that it is only possible to design circular products if information about their EOL processes is available. Therefore, it is crucial first to establish a stable foundation in which EOL realities are considered before creating a CE product design. This brings us to the explanation of the main difference between a linear and a circular economy: in a circular economy, the end customer is no longer the product user but the EOL processes that recycle the products.

## Funding

This research was funded by the Di-Plast project, which is supported by Interreg NWE. The project aims to improve the uptake of recycled plastic material (rPM) within the packaging and building sector.

Find more details about the project Di-Plast at: https://www.nweurope.eu/projects/project-search/di-plast-digital-circular-economy-for-the-plastics-industry/(accessed on November 5, 2022).

## CRediT authorship contribution statement

**Jeff Mangers:** Conceptualization, Data curation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mahdi Amne Elahi:** Methodology, Project administration, Writing – review & editing. **Peter Plapper:** Conceptualization, Funding acquisition, Project administration, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgments

This publication is an extension of the APMS-contribution: Value Stream Mapping (VSM) to evaluate and Visualize Interrelated Process-Chains Regarding the Circular Economy (Mangers et al. 2021).

The authors thank Sri Kolla, Alexej Simeth, Meysam Minoufekr, Mohammad Abuabiah, and Franz Wieck for their valuable input.

## List of acronyms

| | |
|---|---|
| BOL | Beginning-of-Life |
| CAD | Computer-Aided Design |
| CAR | Computer-Aided Recycling |
| CAx | Computer-Aided x |
| CE | Circular Economy |
| DES | Discrete Event Systems |
| DFA | Deterministic Finite Automata |
| DfC | Design for Circularity |
| DfR | Design for Recycling |
| DfX | Design for X |

| | |
|---|---|
| DT | Digital twin |
| EMF | Ellen MacArthur Foundation |
| EOL | End-of-Life |
| GUI | Graphical User Interface |
| ISO | International Organization for Standardization |
| I4.0 | Industry 4.0 |
| NIR | Near-InfraRed |
| PET | Polyethylene Terephthalate |
| PLM | Product Lifecycle Management |
| R.PET | Recycled Polyethylene Terephthalate |
| SC | Supply Chain |
| VSM | Value Stream Mapping |

## References


Acerbi, Federica, Sassanelli, Claudio, Taisch, Marco, 2022. A conceptual data model promoting data-driven circular manufacturing. Oper. Manag. Res., 0123456789 https://doi.org/10.1007/s12063-022-00271-x.

Agrawal, Rohit, Wankhede, Vishal A., Kumar, Anil, Luthra, Sunil, Huisingh, Donald, 2022. Progress and trends in integrating industry 4.0 within circular economy: a comprehensive literature review and future research propositions. Bus. Strat. Environ. 31 (1), 559–579. https://doi.org/10.1002/bse.2910.

Azevedo, Garrido, Susana, Godina, Radu, João Carlos de Oliveira Matias, 2017. Proposal of a sustainable circular index for manufacturing companies. Resources 6 (4). https://doi.org/10.3390/resources6040063.

Busert, Timo, Fay, Alexander, 2019. Extended value stream mapping method for information based improvement of production logistics processes. IEEE Eng. Manag. Rev. 47 (4), 119–127. https://doi.org/10.1109/EMR.2019.2934953.

Chari, Arpita, Niedenzu, Denis, Despeisse, Mélanie, , Carla Gonçalves Machado, Domingues Azevedo, João, Boavida-Dias, Rui, Johansson, Björn, 2022. Dynamic capabilities for circular manufacturing supply chains—exploring the role of industry 4.0 and resilience. Bus. Strat. Environ. 31 (5), 2500–2517. https://doi.org/10.1002/bse.3040.

Ministère de l'Énergie et de l'Aménagement du territoire, du Climat et du Développement Durable Ministère de l'Environnement, and Ministère de L'Economie, 2021. Circular Economy Strategy Luxembourg. https://circulareconomy.europa.eu/platform/sites/default/files/strategy-circular-economy-luxembourg-022021.pdf.

Design, Eco, 2022. Instruction Design for Recycling, vols. 1–8.

Economy Initiative Deutschland, Circular, 2021. Plastics Packaging in a Closed Loop.

ECR, 2021. Packaging Design for Recycling - A Global Recommendation for Circular Packaging Design.

Edtmayr, Thomas, Alexander, Sunk, Sihn, Wilfried, 2016. An approach to integrate parameters and indicators of sustainability management into value stream mapping. Proc. CIRP 41, 289–294. https://doi.org/10.1016/j.procir.2015.08.037.

EPBP, 2022. Design Guidelines, 2022. https://www.epbp.org/design-guidelines.

Erlach, K., 2013. Value Stream Design. Springer Berlin Heidelberg.

EUNOMIA, 2022. PET MARKET IN EUROPE - State Oof Play.

European Parliament and Council of the European Union, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Text with EEA Relevance). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098.

Eurostat, 2021. Packaging Waste Statistics, 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics.

Faulkner, William, Badurdeen, Fazleena, 2014. Sustainable value stream mapping (Sus-VSM): methodology to visualize and assess manufacturing sustainability performance. J. Clean. Prod. 85, 8–18. https://doi.org/10.1016/j.jclepro.2014.05.042.

Favi, Claudio, Germani, Michele, Luzi, Andrea, Mandolini, Marco, Marconi, Marco, 2017. A design for EoL approach and metrics to favour closed-loop scenarios for products. Int. J. Sustain. Eng. 10 (3), 136–146. https://doi.org/10.1080/19397038.2016.1270369.

Galvão, Graziela Darla Araujo, Homrich, Aline Sacchi, Geissdoerfer, Martin, Evans, Steve, scoleze Ferrer, Paulo Sergio, Marly, M., Carvalho, 2020. Towards a value stream perspective of circular business models. Resour. Conserv. Recycl. 162, 105060 https://doi.org/10.1016/j.resconrec.2020.105060. June 2019.

Garza-Reyes, Arturo, Jose, Romero, Joseth Torres, Govindan, Kannan, Cherrafi, Anass, Ramanathan, Usha, 2018. A PDCA-based approach to environmental value stream mapping (E-VSM). J. Clean. Prod. 180, 335–348. https://doi.org/10.1016/j.jclepro.2018.01.121.

Ghoreishi, Malahat, Happonen, Ari, 2020. New promises ai brings into circular economy accelerated product design: a review on supporting literature. E3S Web Conf. 158, 1–10. https://doi.org/10.1051/e3sconf/202015806002.

Grafström, Jonas, Aasma, Siri, 2021. Breaking circular economy barriers. J. Clean. Prod. 292 https://doi.org/10.1016/j.jclepro.2021.126002.

Gusmerotti, Natalia Marzia, Testa, Francesco, Corsini, Filippo, Pretner, Gaia, Iraldo, Fabio, 2019. Drivers and approaches to the circular economy in manufacturing firms. J. Clean. Prod. 230, 314–327. https://doi.org/10.1016/j.jclepro.2019.05.044.

Hartmann, Lukas, Metternich, Joachim, 2020. Waste in value streams caused by information flow: an analysis of information flow barriers and possible solutions. Procedia Manuf. 52, 121–126. https://doi.org/10.1016/j.promfg.2020.11.022.

Hedlund, Christer, Stenmark, Petter, Noaksson, Erik, Lilja, Johan, 2020. More value from fewer resources: how to expand value stream mapping with ideas from circular economy. Int. J. Qual. Serv. Sci. 12 (4), 447–459. https://doi.org/10.1108/IJQSS-05-2019-0070.

Hernandez, Marquina, Maria, Victoria, Zwolinski, Peggy, Mangione, Fabien, 2021. Application of value stream mapping tool to improve circular systems. Clean. Eng. Technol. 5, 100270 https://doi.org/10.1016/j.clet.2021.100270.

ISO, 2020. Value Stream Management (VSM), 22468.

Kalmykova, Yuliya, Sadagopan, Madumita, Rosado, Leonardo, 2018. Circular economy - from review of theories and practices to development of implementation tools. Resour. Conserv. Recycl. 135, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034. October 2017.

Kirchherr, Julian, Reike, Denise, Hekkert, Marko, 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127 (April), 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kuo, Tsai, Chi, Chiu, Ming Chuan, Hsu, Chia Wei, Tseng, Ming Lang, 2019. Supporting sustainable product service systems: a product selling and leasing design model. Resour. Conserv. Recycl. 146 (April), 384–394. https://doi.org/10.1016/j.resconrec.2019.04.007.

Lewin, Marcus, Voigtlander, Sebastian, Fay, Alexander, 2017. Method for process modelling and analysis with regard to the requirements of industry 4.0: an extension of the value stream method. In: Proceedings IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society. https://doi.org/10.1109/IECON.2017.8216677, 2017-Janua: 3957–62.

Lin, Kuo Yi, 2018. User experience-based product design for smart production to empower industry 4.0 in the glass recycling circular economy. Comput. Ind. Eng. 125, 729–738. https://doi.org/10.1016/j.cie.2018.06.023. June.

Lo, C.K., Chen, C.H., Zhong, Ray Y., 2021. A review of digital twin in product design and development. Adv. Eng. Inf. 48 https://doi.org/10.1016/j.aei.2021.101297. July 2020.

Mangers, Jeff, Oberhausen, Christof, Minoufekr, Meysam, Plapper, Peter, 2020a. Creation of an ISO standard at the example of value stream management method. In: Jakobs, Kai (Ed.), Shaping the Future through Standardization. IGI Global, pp. 1–26. https://doi.org/10.4018/978-1-7998-2181-6.ch001.

Mangers, Jeff, Lou, Thoussaint, Minoufekr, Meysam, Plapper, Peter, 2020b. Multi-Level Information Value Stream Mapping, pp. 147–156.

Mangers, Jeff, Minoufekr, Meysam, Plapper, Peter, 2021a. Value stream mapping (VSM) to evaluate and visualize interrelated process-chains regarding circular economy. In: IFIP Advances in Information and Communication Technology, 633 IFIP. Springer International Publishing. https://doi.org/10.1007/978-3-030-85910-7_56.

Mangers, Jeff, Minoufekr, Meysam, Plapper, Peter, Kolla, Sri, 2021b. An Innovative Strategy Allowing a Holistic System Change towards Circular Economy within Supply-Chains.

Merli, Roberto, Preziosi, Michele, Acampora, Alessia, 2018. How do scholars approach the circular economy? A systematic literature review. J. Clean. Prod. 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112.

Meudt, Tobias, Metternich, Joachim, Abele, Eberhard, 2017. Value stream mapping 4.0: holistic examination of value stream and information logistics in production. CIRP Ann. - Manuf. Technol. 66 (1), 413–416. https://doi.org/10.1016/j.cirp.2017.04.005.

Moreno, Mariale, De los Rios, Carolina, Rowe, Zoe, Charnley, Fiona, 2016. A conceptual framework for circular design. Sustainability 8 (9). https://doi.org/10.3390/su8090937.

Pagoropoulos, Aris, Pigosso, Daniela C.A., McAloone, Tim C., 2017. The emergent role of digital technologies in the circular economy: a review. Proc. CIRP 64, 19–24. https://doi.org/10.1016/j.procir.2017.02.047.

Pozo Arcos, B., Balkenende, A.R., Bakker, C.A., Sundin, E., 2018. Product design for a circular economy: functional recovery on focus. Proc. Int. Des. Conf. Des. 6, 2727–2738. https://doi.org/10.21278/idc.2018.0214.

Preut, Anna, Kopka, Jan Philip, Clausen, Uwe, 2021. Digital twins for the circular economy. Sustainability 13 (18). https://doi.org/10.3390/su131810467.

RecyClass, 2022. Design for Recycling Guidelines, 2022. https://recyclass.eu/recyclability/design-for-recycling-guidelines/.

Rosa, Paolo, Sassanelli, Claudio, Urbinati, Andrea, Chiaroni, Davide, Terzi, Sergio, 2020. Assessing relations between circular economy and industry 4.0: a systematic literature review. Int. J. Prod. Res. 58 (6), 1662–1687. https://doi.org/10.1080/00207543.2019.1680896.

Rother, Mike, Shook, John, 1999. Learning to See: Value Stream Mapping to Add Value and Eliminate Muda (Lean Enterprise Institute). Lean Enterprise Institute Brookline. https://doi.org/10.1109/6.490058.

Rowley, Jennifer, 2007. The wisdom hierarchy: representations of the DIKW hierarchy. J. Inf. Sci. 33 (2), 163–180. https://doi.org/10.1177/0165551506070706.

Saidani, Michael, Harrison, Kim, 2021. Design for product circularity: circular economy indicators with tools mapped along the engineering design process. In: *Design for Manufacturing and the Life Cycle Conference (DFMLC)* 26.

Saidani, Michael, Bernard, Yannou, Leroy, Yann, Cluzel, François, Kendall, Alissa, 2019. A taxonomy of circular economy indicators. J. Clean. Prod. 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Sassanelli, Claudio, Urbinati, Andrea, Rosa, Paolo, Chiaroni, Davide, Terzi, Sergio, 2020. Addressing circular economy through design for X approaches: a systematic literature review. Comput. Ind. 120 https://doi.org/10.1016/j.compind.2020.103245.

Sassanelli, Claudio, Da Costa Fernandes, Sânia, Rozenfeld, Henrique, Mascarenhas, Janaina, Terzi, Sergio, 2021. Enhancing knowledge management in the PSS detailed design: a case study in a food and bakery machinery company.

Concurr. Eng. Res. Appl. 29 (4), 295–308. https://doi.org/10.1177/1063293X21991806.
Schaik, Antoinette van, Reuter, M.A., 2013. Product Centric Simulation Based Design for Recycling (DfR) - 10 Fundamental Rules & General Guidelines for Design for Recycling. NVMP/Wecycle. https://doi.org/10.13140/RG.2.2.26343.44965. August.
Suárez-Eiroa, Brais, Fernández, Emilio, Méndez-Martínez, Gonzalo, Soto-Oñate, David, 2019. Operational principles of circular economy for sustainable development: linking theory and practice. J. Clean. Prod. 214, 952–961. https://doi.org/10.1016/j.jclepro.2018.12.271.
Toxopeus, M.E., Van Den Hout, N.B., Van Diepen, B.G.D., 2018. Supporting product development with a practical tool for applying the strategy of resource circulation. Proc. CIRP 69, 680–685. https://doi.org/10.1016/j.procir.2017.11.033.
Ulrich, Hans, 1984. *Management*. Schriftrei, Stuttgart.
Union, European, 2018. Directive (EU) 2018/852 of the European parliament and of the Council of 30 may 2018 amending directive 94/62/EC on packaging and packaging waste. Off. J. Eur. Union (November 2008): 141–54. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0852.
Vajna, Sándro, Weber, Christian, Zeman, Klaus, Hehenberger, Peter, Gerhard, Detlef, Wartzack, Sandro, 2018. CAx Für Ingenieure - Eine Praxisbezogene Einführung. Springer. Vieweg. 3. Auflage.
Vossen, Gottfried, Witt, Kurt-Ulrich, 2016. Grundkurs Theoretische Informatik. Grundkurs Theoretische Informatik. https://doi.org/10.1007/978-3-8348-8155-7.
Wang, Xi Vincent, Wang, Lihui, 2019. Digital twin-based WEEE recycling, recovery and remanufacturing in the background of industry 4.0. Int. J. Prod. Res. 57 (12), 3892–3902. https://doi.org/10.1080/00207543.2018.1497819.