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Green Gateways: a concept for decisions in Circular-Oriented Economies

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Abstract

Industrial technologies have evolved towards circular-oriented manufacturing. New approaches in the management of production systems are needed to guarantee the success of such a circular approach. This paper identifies three research questions related to the complexities of decision-making within CEs and defines the concept of Green Gateways in the circular economy. A Green Gateway is a type of decision that supports to realizing the full potential of products and materials. Indeed, the potential value of products and materials must be assessed and leveraged and the concept of Green Gateway will be useful to identify common decisions and to define a common framework in the future. The integration of digital information and digital twins of products, processes, and circular value and supply chains emerges as a key factor in guiding decision-makers effectively, especially for Green Gateways where adequate information, tools and methods must be used to manage value retention options, product flows, production and pricing decisions jointly with the multiple objectives of profitability and sustainability. Additionally, this paper explores specific examples of circular economy use cases, drawing attention to their similarities and highlighting key insights.

Keywords: Circular Economy; Manufacturing; Decision making; Digital twin.

1. Introduction

The shift towards a Circular Economy (CE) presents a global growth opportunity as highlighted by many recent reports [1, 3, 17]. Evolving from traditional linear models to new and improved circular models is highly important [3]. However, the shift toward a circular economy complicates the management of manufacturing systems by intensifying the complexity of flows and incorporating greater variability and uncertainties in customer demands, product and process design, and technologies.

Fully circular approaches may also encounter significant technological barriers [3, 17]. In order to eliminate these barriers, CE needs specific technological enablers to empower the capability to close the circles. Among these enablers, digitalisation has a pivotal role [2, 9]. According to Gartner in 2018 [7], the 13% of manufacturing industries employ Digital Twins (DTs), digital replicas of physical systems, and the 62% of them are in the process of adopting. Thus, in the natural evolution of decision-making processes, companies will be supported by Digital Twins (DTs), enabling them to make environmentally friendly decisions. Consequently, companies will unlock their full potential for achieving a true zero-waste circular economy and reduce their dependency on raw materials.

The work proposed in this paper relates to the need of rapid decision-making in CE networks enabling companies to make data and DT-based decisions. In detail, the paper identifies three research questions and defines the concept of *Green Gateways* as a type of decision in the CE that is related to *Value-Retention Options* (ROs). Value Retention Options, such as *remanufacture* and *recycle*, are complementary processes and activities that preserve both material value and functionality within the product. If pursued strategically, these options can expedite the transition from a linear to a circular economy.

1.1. Value-retention option (ROs)

The concept of the CE has garnered increasing attention in the past decade. The literature has employed various terms concerning ROs and processes related to circularity [14, 11]. ROs are referred using terms prefixed with *‘re-’* from Latin, signifying concepts like *again, back, afresh, anew* which captures the essence of the CE [15].

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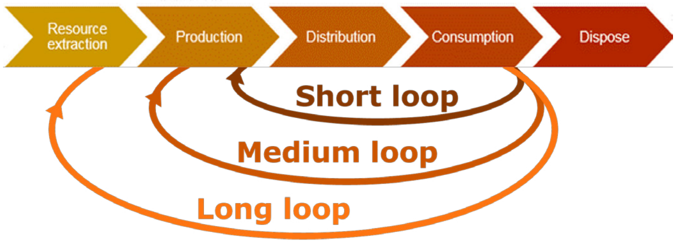

Fig. 1. Illustrative representation of short, medium, and long loops in CE.

As the definition of Retention Options (ROs) varies across cases, this paper, for the sake of clarity, adopts the well-established terminology provided by the Ellen MacArthur Foundation [8].

Frameworks available in the literature include from 3 to 11 ROs; nevertheless, there is no clear trend visible from the use of simpler ones (3Rs) to more nuanced typologies (up to 11Rs) over the years. As an example, one of the 4-R framework [10] considers *Repair, Refurbish, and Remanufacture* as possible product back-loops that increase product life time and a final *Recycle* option at product End-Of-Life (EOL) to retain value as recycled materials. Providing a hierarchy among ROs is common, and it is clear also from the provided example where *Repair, Refurbish, and Remanufacture* are options requiring an increasing transformation effort onto the product.

Figure 1 represents three main CE loops that have been identified as short, medium and long loops [14]. Under the paper domain of interest, the *short, medium,* and *long* loops respectively include two, three, and two ROs as described in Table 1.

The level of circularity increases from short to long loops. In short loops, products recirculate with minimal re-processing. Conversely, long loops involve numerous actors, a multitude of products and materials, and often follow the "linear" sequence of processes in their re-circulation.

RO	Definition	Loop
Reuse / Resell	To *Reuse* the products for their intended purpose or to *Resell* the products to other markets	Short
Repair	To *Repair* products to a usable state to fulfill their intended use	Short
Refurbish	To *Refurbish* products to good working order, e.g. replacing components, updating specifications, improve appearance	Medium
Remanufacture	To *Remanufacture* products to as-new conditions trough a re-engineering process	Medium
Repurpose	To *Repurpose* products (or their components) in new products with a different function	Medium
Recycle	To *Recycle* products to re-obtain their basic materials	Long
Recover	To *Recover* energy embodied in waste	Long

Table 1. Classification of Value Retention Options (ROs) in short, medium, and long loops and related definition.

1.2. Addressing decisions in CE

Research in the field of the CE is still in its early stages. Despite significant opportunities for quantitative modeling in value creation and applications in real-life case problems, the CE research field has primarily emphasized empirical qualitative research implications [6]. Moreover, it has predominantly relied on traditional data analysis techniques and models, such as content analysis, life cycle analysis, and statistical analysis techniques [12]. Limited attention has been devoted to the implication of advanced data analysis techniques, such as correlation analysis, regression analysis, and network analysis [12].

Furthermore, CE-related research has not fully embraced dynamic data-driven multi-criteria decision-making (MCDM) techniques, despite their necessity in making optimal decisions when multiple criteria are involved in addressing various sustainability-related problems in real-time.

Manufacturing industries and other actors in the CE often operate their production and logistic facilities using simplistic models based on the traditional linear economy or relying on limited information available with the product. Instead, in the CE, various product types at different usage stages circulate within loops and products entering CE loops at different stages of their life-cycle are associated with distinct prices. In such an environment, making joint decisions on production and pricing could yield significant benefits [5].

For example, in the electric mobility battery market, actors can choose between battery refurbishing or recycling based on specific item histories, inventory levels, order execution status in the value chain, and appropriate prices for new, refurbished, and remanufactured products.

From a mathematical point of view, CE requires to solve multidimensional sequential decision making problems with nonlinear functions and uncertainties about the modeling of the other actors and possible disruptions [13]. Approximate dynamic programming and Reinforcement Learning are effective and efficient techniques for addressing sequential decision-making problems. However, implementing them in real-life scenarios presents challenges due to problem dimension (curse of dimensionality) and the time required to train Reinforcement Learning models based on system observations [4], a concern particularly relevant in the context of the circular economy.

1.3. Related research questions and challenges

In navigating the complexities of decision-making within CEs, three key research questions emerge, each addressing different aspects of the complex landscape in the CE.

RQ1 – How can common decisional problems associated with product value retention options (ROs) in CE be discerned, taking into consideration the peculiarities inherent each RO?

As for the first research question, *RQ1*, to recognize the nuances of each RO is imperative for establishing a comprehensive mapping of decisions related to product value retention within the circular economy. Thus, a common mapping of RO-related decisions in the CE is needed.

RQ2 – How to make production, logistics, and pricing decisions based on real-time process data in CE?

Moving on to *RQ2*, the focus shifts to the real-time processes within the CE. The integration of digital information and digital twins of products, processes, and circular value and supply chains emerges as a key factor in guiding decision-makers effectively. The question investigates the strategies and methodologies required for making informed and optimized decisions in the realms of production, logistics, and pricing based on real-time process data. Novel sequential decision-making methodologies are needed for deriving the optimal production, logistic, and pricing strategy of actors operating at decisional points.

RQ3 – How decision-makers in circular manufacturing value chains can enhance their capabilities?

The third research question, RQ3, explores ways to effectively meet the demands of circular economies by developing techniques to integrate optimal strategies into the Digital Twin (DT) of the circular economy. Similarly, techniques that allow for the continuous comparison of the actual process behavior with DT-obtained estimates should be developed ensuring alignment with evolving circular economy dynamics.

In summary, this exploration of three research questions aims to simplify decision-making processes in CEs. It provides insights and methodologies to propel the field toward more informed, adaptive, and sustainable practices.

The challenges in addressing these research questions are linked to estimating the remaining potential value of a product, for example involving techniques such as Life Cycle analysis, and to understanding the customer choice model, which correlates product characteristics and prices based on acquired data.

2. The Green Gateways

CE requires the management of product flows going through different loops (or orbits) for multiple times; thus gateway-related decisions need to be properly managed to achieve advantageous decisions. The new concept of *Green Gateways* represents these types of decisions.

> *A Green Gateway is a type of decision to be addressed in the circular value-chain allowing companies to realize the full potential of products and materials for a zero-waste Circular Economy while making environmentally conscious decisions.*

In the transition from a linear economy to a CE, the potential remaining value that a product might maintain after a first usage phase (i.e. product consumption phase in Figure 1) is extracted by opening the gate towards the short, the medium or the long loop instead of disposing the product. The overall goal is aligned with CE principles of zero-waste and environmentally conscious value-chains. However, the decision is complex and relies on multiple indicators associated with product expected remaining value and with the expected cost of the selected value-retention option (RO).

> *The Green Gateway appears when a decision such as Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, or Recovery a certain product or material is faced and, respectively, for decisions such as where to procure a certain product or material.*

From the product perspective, the Green Gateways opens/closes routes from/to different processes and into different loops with significant impact on product value and overall lifetime. From the process perspective, the Green Gateways allows/interrupts arrivals of parts, enables the production and release of a certain part type at a given time. Indeed, the Green Gateway might be related to products to be processed or sold and, respectively, to products (or materials) to be procured as input for a certain process. Clearly, inventory management decisions are Green Gateways.

The nature of CE implies that, during the item lifetime, the Green Gateways occur multiple times when the part arrives at a particular location in the value chain. Also, the Green Gatways include decisions related to the management of one or more RO loops according; thus the decisions might come around continuously.

> *The Green Gateway concept links to discrete- or continuous-time decision-making processes with possibly multiple actors involved in the multi-objective decisional process including both quantitative and qualitative criteria.*

In a complex decision-making situation, there are multiple answers that warrant further experimentation before committing to a single approach. The difficulty of addressing a multi-objective optimization is clearly a challenge at Green Gateways where some of the criteria might not be quantified nor ranked. In addition, multi-actor systems might require different visions of the problem and shared decisions to be managed.

> *In order to operate practically, the Green Gateway needs data, methods and tools to facilitate and support the making of effective choices employing different technologies to aid the decision makers in the decision process.*

An illustrative representation of how the Green Gateway operates practically is provided in Figure 2. The gate-decision appears at a node in the CE (green circle) where one or more ROs are involved. The interaction between the decision maker(s) and the structure supporting the Green Gateway operation is represented in the right-hand side of the Figure 2. A set of tools and methods, grounded on available data and models, enables the digital representation of the CE needed for the Green Gateway. To properly support the decision-making process, the interaction consists in providing queries and receiving predictions, indicators, and scenarios. Alternatives are provided to the decision maker(s), according to multiple selected criteria, and choices of decision maker(s) are applied at the gate as a consequence. Thus, timely and efficient decisions can be taken as essential to the smooth operation of the network.

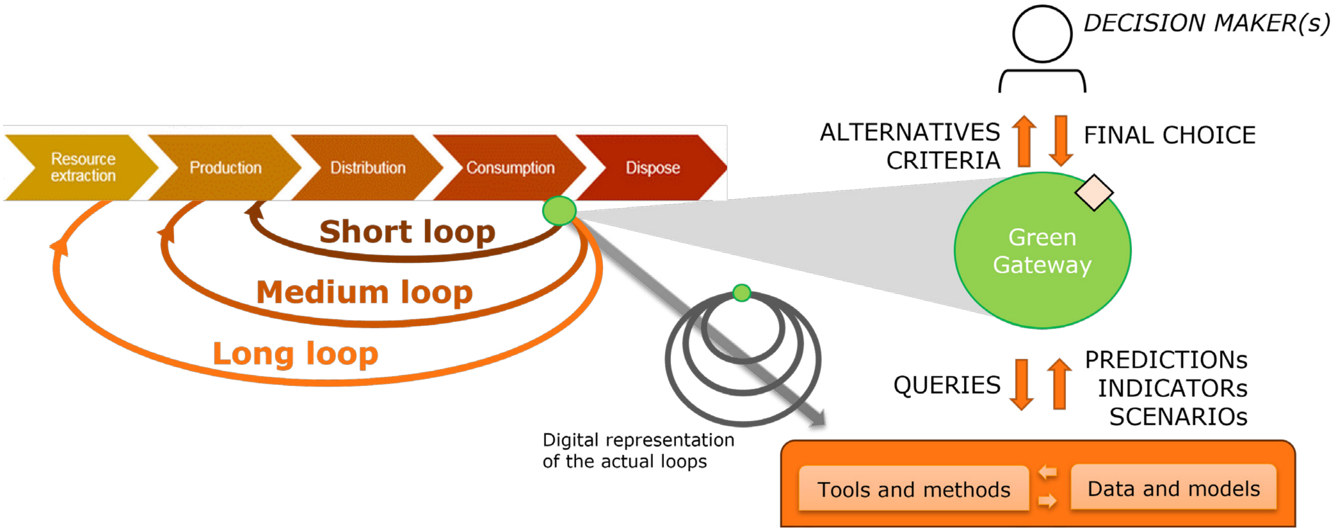

Fig. 2. Illustrative representation of the Green Gateway

The Green Gateway may require knowledge on system state, estimates of system behavior and risk evaluations and, given both the complexity and the dynamic of the systems under study, it is of paramount importance to avoid model obsolescence and to exploit system digitalization and data-driven solutions. Such features can be provided by properly developed DTs and by a set of tools and methods that maintains accurate models, provides scenarios and performance predictions at the proper fidelity level to guide the decision makers toward system improvement.

In addition, to maintain a proper alignment between DTs and the physical counterpart, the Green Gateway needs synchronization activities. Such synchronization avoids model obsolescence, reduces the risk of misalignment between the digital and the physical counterparts, and the forecast bias [16].

3. Application case studies

We provide the description of three case studies as examples of CE in different fields of application.

3.1. Sterilization of medical devices

The sterilization of medical devices (MDs) is a critical process for hospitals and clinics. MDs need to be properly sterilized and maintained after each use and must be available to meet service targets. The strict constraints and uncertainty in MD usage make the operative management of the sterilization department highly complex. Also, data associated with the tracking of the MDs and on the sterilization processes are highly important in health care applications.

Figure 3 illustrates the case study: to sterilize MDs enables their repetitive usage and the case study is considered as a *Repair* example. The sterilization center conducts a quality analysis on MDs to route them toward maintenance activities(*Refurbish*), if worn MDs can be restored, or toward a *Recycle* option, if worn MDs are at their EOL. *Refurbish* and *Recycle* loops are in grey color in Figure 3 being out of company's scope. The identified GG are represented as green circles.

The management of the sterilization center requires accurate performance predictions to improve resource and operator workload. Kits composed of different MDs populate the loop. Thus, the large product mix, combined with the highly manual nature of processes and numerous constraints, makes problem modeling challenging. In addition, the choices made in the sterilization center can significantly impact the hospital's performance, and vice versa. The first Green Gateway (GG#1 in Figure 3) concerns the operative management of the center (i.e., *Repair*), as the manager must decide which MD (or kit) should be processed at a given time based on hospital requirements and the current status of the center in terms of resource utilization and operator workload.

The second Green Gateway (GG#2 in Figure 3) is the management of worn MDs and occurs during MD inspection, as worn MDs might be kept in the loop or might enter the medium loop of refurbish (e.g., resharpening of tools) or the long loop of recycle. Postponing the gateway opening towards medium/long loops increases the probability of unwanted breakages, while an early decision might result in a waste of product value.

The third Green Gateway (GG#3 in Figure 3) involves decisions on the management of MDs and kits, such as the creation of new kits or the reintegration of a worn (or lost) MD into an existing kit. Incompleteness in a kit causes a delay in the sterilization process because the kit cannot proceed, risking stock-out of sterile kits and jeopardizing the sterilization service to the hospital.

3.2. Rethinking of battery cells

The second case study focuses on the EOL management of battery cells. The company collects used battery cells and repurpose them for novel applications by assembling new battery packs. The produced battery packs are collected after usage and

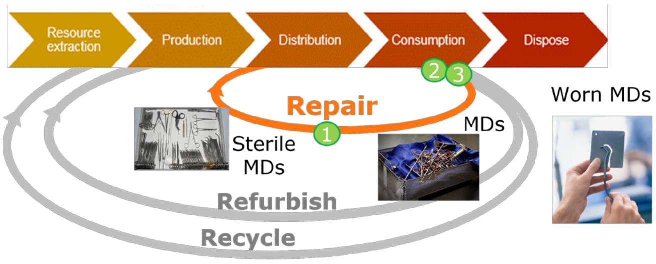

Fig. 3. Case study: Medical device sterilization

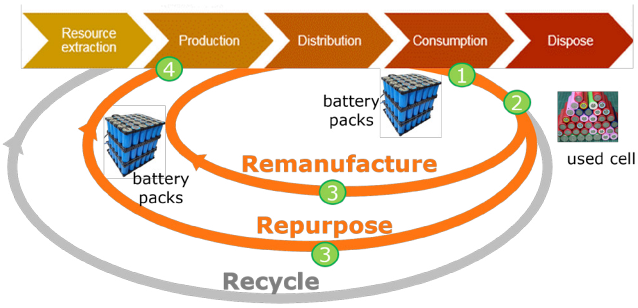

Fig. 4. Case study: Rethinking of battery cells

remanufactured according to their remaining value so that cells might be replaced to restore the battery pack capacity.

Figure 4 illustrates the case study: the *Remanufacturing* and *Repurpose* options, both medium loop ROs, are highlighted in orange and the identified GG are represented as green circles. The *Repurpose* options is used when cells start a new life in a battery pack, whilst the *Remanufacture* option is used to restore battery packs capacity.

The actual state of health of batteries (SOH) and their remaining useful life (RUL) is challenging to predict and significantly affects the system's performance. Hence, product-oriented Digital Twins (DTs) are needed to support operative decisions. Data related to the usage of battery packs are collected and will be used to create product oriented DTs to estimate, for example, usage profile, SOH and RUL of the pack.

The first Green Gateway (GG#1 in Figure 4) involves the collection and management of battery packs to be remanufactured. Similar to the sterilization center case, postponing the gateway opening towards the medium loop increases the probability of unwanted disruptions, while an early decision might waste product value by starting a remanufacturing process that is not needed yet.

The second Green Gateway (GG#2 in Figure 4) involves decisions on the management of the input flow (battery packs and used cells). Both cells and packs are tested, and each must pass a quality check, resulting in an estimation of the SOC and the RUL. Used cells can be repurposed to create new battery packs or can substitute some cells in an existing pack that needs remanufacturing. Whenever a cell is considered at its EOL, the *Recycle* loop should be opened (grey loop in Figure 4 since it is not part of company's scope). As previously discussed, postponing or anticipating the decision might have a significant effect.

The third Green Gateway (GG#3 in Figure 4) involves the operative management of the production system (i.e., *Repurpose* and *Remanufacture*), as the manager must select which pack should be processed at a given time and how to assemble cells to increase pack expected performance.

Dynamic pricing decisions and inventory management decisions are the fourth Green Gateway (GG#4 in Figure 4). Sales prices of remanufactured and brand-new batteries must be determined based on on-hand stocks. Dynamic pricing is typically based on changes in real-time product supply and demand, and one of its main advantages is to enable leveraging demand and managing on-hand stocks efficiently.

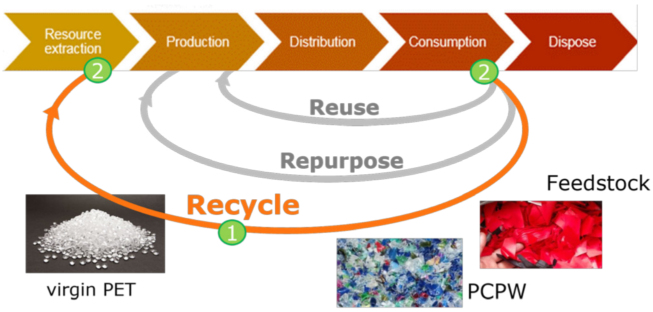

Fig. 5. Case study: PET recycling

3.3. PET Endless Recycling

Recycling is one of the most important RO of CE avoiding the landfill-crane of materials. The chemical recycling of PET from post-consumer plastic waste (PCPW) and textile (feedstock) is considered as the core RO of the use case. Specifically, flows of input materials (PCPW and feedstock) are recycled to obtain virgin PET to be reinserted in the market. Figure 5 represents the case study: the *Recycle* option, as long loop RO, is highlighted in orange and the identified GG are represented as green circles. Grey loops (short and medium) include from the *Reuse* to the *Repurpose* ROs and, despite connected, are out of company's scope.

The semi-batch nature of the chemical process poses a challenge to classical problem modeling. Product impact assessment and digital passports are crucial to ensuring the valuable upgrade of the recycled material flow. Decision-making in this case study should be supported by advanced Digital Twins (DTs) capable of capturing the complex interactions within the plant to optimize its operation. Real-time data collected from sensors at the chemical plant can be used for data-driven modeling to obtain an accurate representations of the plant state and to obtain accurate estimates of system behavior.

The first Green Gateway (GG#1 in Figure 5) refers to decisions for the plant operative management including the selection of the mix/product variant to be produced based on the system state (e.g., inventory levels, current production) and the management of all processes involved in the recycling (sorting, pre-processing, depolymerization, etc.). Special attention is required for reconfigurations (changes of mix/variant) to maintain the thermochemical process equilibrium point, which may change with variations in the product mix/variant, and to ensure a smooth transition.

The second Green Gateway (GG#2 Figure 5) encompasses decisions on the inventory management of input products (PCPW and feedstock) and the management and pricing of obtained output material (i.e. virgin PET). A stockout of input products may compromise the efficiency of the continuous chemical process. The problem also includes product allocation to a specific storage and the replenishment rule, which may depend on the market for input/output materials.

4. Conclusive remarks and future developments

This work defines the concept of Green Gateways in the field of Circular Economy (CE)-related decision-making problems. The Green Gateway, as a concept, helps in recognizing critical decisions that are peculiar in CE. In particular:

- A Green Gateway is a type of decision to be addressed in the circular value-chain;
- A Green Gateway is environmentally conscious;
- A Green Gateway aims at realizing the full potential of products;
- A Green Gateway is related to increasing the value of ROs, such as Reuse and Repair (short loop), Refurbish, Remanufacture, and Repurpose (medium loop), Recycle, and Recovery (long loop);
- A Green Gateway employs different technologies to aid the decision makers.

Future effort will be devoted to the development of a framework based on the concept of Green Gateways with the goal of highlighting the similarities among ROs and the peculiarities of each option. In relation to RQ1, the Green Gateway (GG) concept also highlights the need for new models capable of representing non-linear value chains and potentially applicable in multiple fields while considering the different Value-Retention Options (ROs) involved.

As for the RQ2 and RQ3, the integration of digital information and digital twins of products and processes is a key lever of improvement. Once Green Gateways are identified, their practical operation should make use of updated models, to avoid obsolescence, and of accurate estimates, to improve decisions. The Green Gateways concept will help in understanding and selecting methods and tools to be used, common practical problems, benchmarks models and results.

The imperative for advanced modeling, analysis, and optimization methods to aid decision-makers in Green Gateways is crucial. Furthermore, the application of AI machine learning and process mining approaches will play a key role in formulating new algorithms that extract essential correlation structures among products, processes, and actors through continuous data collection. Future endeavors will focus on advancing optimization methods within the dynamic programming and reinforcement learning framework. This involves integrating multi-dimensional criteria analysis and incorporating simulation predictions derived from advanced Digital Twins (DTs).

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