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Towards a Data Classification Model for Circular Product Life Cycle Management

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Abstract. Nowadays, due to the limited availability of resources, the adoption of sustainable practices is gaining importance, especially while dealing with the manufacturing sector that is considered one of the most resource greedy sectors. To cope with this issue, a new sustainable and industrial economy, called “circular economy” arisen. The diffusion of this economy can be eased by the advance management of data and information. Nevertheless, from the extant literature emerged some criticalities regarding information management flows while dealing with circular economy strategies adoption. Indeed, the present work aims to first identify the main criticalities in information management while adopting circular economy principles, and second to investigate the decisions, and the related data and information required to make these decisions, that manufacturers have to undertake to enable the circular product life cycle management. To achieve this goal, the present work relies on scientific literature. This choice enables to grasp the widespread knowledge developed by scholars about these concepts, by individualizing the main decisions that should be taken by the company internal stakeholders, to manage circular products, being affected by external stakeholders’ behaviours and decisions along product life cycle. Therefore, this work aims to support circular product life cycles management and, this objective has been achieved through the development of a data classification model.

Keywords: Circular Economy, Product Life Cycle Management, Decision-making process.

1 Introduction

Nowadays, the huge increase in product demand by consumers is increasing the number of resources consumed, which leads to both municipal and industrial waste generation intensification [1]. To cope with this issue, some countermeasures have been proposed also by policymakers, among which the definition of the *sustainable development goals* that are urgent actions to be undertaken by the society as a whole [2]. Among these actions, it is stated the importance to promote a more responsible production and consumption, which is aligned with a new economy recently arisen. It is called “circular economy”, being an industrial economy that is designed on purpose to be regenerative

and restorative, is gaining importance for both scientific literature and industry [3]. Moreover, its adoption has been recently encouraged by policymakers too, in particular by the European Commission, through the promotion of new action plans [4]. Indeed, this economy aims to enable the efficient usage and restoration of resources by slowing, closing and narrowing resources loops [5] and, to address this goal, it is based on five main principles: (1) design out waste, (2) build resilience through diversity, (3) rely on energy from renewable resources, (4) think in systems and (5) waste is food [6].

To enable the successful implementation of this economy and fulfil the goal of regenerating resources at the end of their life cycle, manufacturers need to be aware about the importance to ensure an appropriate management of the entire product life cycle [7]. Product life cycle management is traditionally defined as “*the management of all the business processes and associated data generated by events and actions of various lifecycle agents (both human and software systems) and distributed along the product's lifecycle phases*” [8]. Under a circular economy perspective, even further, monitoring each stage of the product life cycle through adequate data gathering is gaining momentum. Indeed, considering that circular economy adoption is sustained also by appropriate information flows [9], the information and data required to be gathered should enable the producer to design the product in order to facilitate its subsequently circular management. Thus, by allowing, at the end of product life cycle, the wider possibility to reuse, remanufacture, recycle or regenerate somehow the product or its components. Indeed, in the present work, information and data considered to be gathered, should be made circulate with the objective to facilitate the closing of resource loops, and from this intention, the concept of “circular” product life cycle management.

Actually, in the extant literature, the most diffused barrier identified for the adoption of circular economy in manufacturing and thus, the appropriate management of product along their life cycles, regards data and information management [10]. Nevertheless, data and information are fundamentals to support an appropriate decision-making process [11], and in line with that are considered one of the most important resources in circular economy [9]. At the best of the authors' knowledge more narrowed researches have been performed to streamline information management, such as the ontological framework for Industrial Symbiosis [12] or for product life cycle management but without including circular economy considerations [13].

Being not yet developed a comprehensive work covering this barrier in circular economy, the present work aims to first envisage what are the main criticalities of information management while dealing with circular product life cycle management and second, it aims to identify the main decisions to be take and to clear out what are the most influencing stakeholders on the manufacturer decision process. All these findings will end up with the development of a preliminary data classification model. In particular, in the model are reported the most relevant decisions to be taken at the beginning of product life cycle which look towards the implications arising during the next stages of the product life cycle. Moreover, this contribution, with the model development, aims to put the basis for future researches towards the coverage of information management criticalities emerged in the extant scientific literature.

To conclude, the paper is structured as follows: (ii) Section 2 reports the main objective of the present work and, the used research methodology to address the objective,

(iii) Section 3 presents the review developed about the major decisions required for the circular product life cycle management through which are highlighted the main information management criticalities, (iv) Section 4 the preliminary data classification model is proposed, explained and discussed as a result of the scientific literature review, (v) Section 5 figures-out suggestions for future researches and, the main limitations of the work.

2 Research Objective and Methodology

The present work aims to identify the main information management criticalities according to the extant scientific literature and to provide a first attempt of a data classification model, to put the basis to streamline information management and facilitate circular product life cycle management decision process. This objective is boosted by the barrier identified in the extant literature in terms of data and information management while adopting circular economy strategies.

This research objective has been addressed by relying on the scientific literature. In particular, Scopus was used as search engine, being it the most diffused engine in industrial engineering. It was queried by using the following keywords: (((("knowledge" OR "information" OR "data") AND "management") OR ("semantic*" OR "ontolog*" OR "data integr*")) AND ("circular economy" OR "close-loop") AND ("Remanufacturing" OR "Recycling" OR "Reuse" OR "Reduce" OR "Redesign" OR "Recover") AND "manufacturing"). No-time frame was used and the only filter introduced was limiting the research on English-written documents. In the sample of papers identified, the ones selected for the analysis were those concerning products and their management under a circular economy perspective, the other were discarded being not coherent with the research focus

Through the literature review it was possible to identify the most diffused criticalities regarding information management and to understand the knowledge, the information, and the data required to support the decision process in adopting circular economy strategies by manufacturing companies. Therefore, this review enabled to identify the major decisions that manufacturers have to take while dealing with circular product life cycle management and, to envisage the broad number of stakeholders involved along the product life cycle that concurrently affect the decision process. As it will be reported in the next sections, both external and internal stakeholders generally impact manufacturers decision process whenever circular economy strategies are adopted in manufacturing companies. In particular, internal stakeholders, e.g. business functions, need to take decisions at the beginning of the product life cycle by balancing their internal objectives and, by taking into account the external stakeholders' objectives and behaviours along the product life cycle.

Once these decisions had been defined and, the main stakeholders affecting these decisions were determined, it was possible to investigate what data were required in order to take the aforementioned decisions. Indeed, the decision process relies on specific knowledge, which requires to take into account the different behaviours and objectives of the stakeholders involved along the product life cycle. The key point ensuring to rely

on the right knowledge is to have appropriate information that is gathered through specific data. This is the reason why data are gaining momentum in circular economy.

Last, through this review, a preliminary data classification model was developed to put the basis to cover the emerged criticalities, concerning information and data management, especially the semantic and the managerial ones.

3 A Review about Knowledge, Information, and Data Enabling Circular Product Life Cycle Management

In the extant scientific literature, one of the most diffused barriers, encountered by manufacturers in exploiting the potentialities of circular economy, concerns data and information management [10]. This is reflected in the creation, exchange, and exploitation of data and information [14], within and outside firms' boundaries, to support the manufacturers' decision-making process [11]. For years, end of life (EoL) strategies to enable resource loops have been addressed in the extant literature, since EoL it has been always considered the joint stage to ensure to close the loop. More recently, it has been understood how much the previous stages, Middle of Life (MoL) and Beginning of Life (BoL), influence the resource circularity potentialities [15]. Therefore, the appropriate management of the "end" of the product life cycle corresponds to the possibility to subsequently reintroduce waste, coming for the product, as a resource for a new cycle, but the product conditions at the EoL are affected by the design of the product [16] and the product usage [17]. From this, the importance to study the circular product life cycle management. This concept is close to the one of closed-loop product life cycle management [18] since, data are gathered from each stage of product life cycle to feedback the system, but in this case, the aim is to enable to facilitate the adoption of circular economy principles. Therefore, leveraging on the three standard moments of the product life cycle: BoL, MoL and EoL [19], from the extant literature it was observed the need to harness the knowledge gathered from each stage, to support the decision process of manufacturers by enabling them to design circular products and appropriate services [20] from the beginning. This would facilitate to empower the BoL towards product circularity, being this stage considered the one which determines most of the future environmental impacts [21]. Indeed, all the stakeholders impacting on the decision-making process of manufacturers should be considered from the foundation, to enable the producer to take adequate decisions [22], especially while dealing with the adoption of circular economy strategies in which the EoL is widely affected by the previous stages [15].

Starting from the product EoL, at this stage the product might be disposed becoming waste rather than reintroduced in a new cycle as a resource [23]. This latter requires to evaluate the product damage level and remaining useful life [24], once brought back, in order to decide whether it is possible its direct reuse or not. In case product direct reuse would not be possible, the second evaluation should concern the investigation about the possibility to disassemble the product together with the relative time and costs required [25]. In the case of a positive response, the evaluation is on the possibility to

remanufacture the product and/or to recycle the product's components. These issues require respectively to find a supplier of substitute components to remanufacture the product ensuring the quality of the remanufactured product [26], and to find an industrial actor responsible to recycle the product components and materials. The reusability, re-manufacturability or recyclability of products might be affected by technical issues but also by consumers' demand for refurbished products [27], for this reason is required to be able to stimulate the market and thus, to create the demand of refurbished products through adequate marketing plans. All the choices taken at the EoL are also influenced by economic considerations, which are used to define whether a strategy could be adoptable or not and how the product could be designed in the future to ease its circularity [11], [28].

At the MoL stage, the product damage level and its remaining useful life are determined. Indeed, customers' behaviour impacts a lot on these issues. Nevertheless, customers' behaviours are affected on one side by their needs, expectations and personal income [21], but on the other side also by the services offered by the manufacturer itself to the user for extending the product life cycle [29]. The product quality maintenance is the target of the manufacturer actions while delivering maintenance services. Indeed, a deep analysis on the product, gathering data also from its life cycle, to investigate the potentialities to repair it or to substitute the ruined components is conducted in order to ensure its original conditions and extending its useful life [30].

Customers' behaviours at product MoL can be influenced by the right definition of product features and functionalities designed during the design phase [31] thus, defined at the BoL stage. To enable the uncontrollable disposal of still functional products, the product modularity should be designed to allow product updated and reuse. Moreover, to empower the product reverse flow, it is first necessary to design the appropriate closed-loop networks [32], but together with this, a successful outcome is also influenced by the product features. Indeed, specific features should be thought at the design phase, such as the possibility to disassemble the product [15] either to substitute not functioning components by remanufacturing the product [33] or to recycle the components [34]. This latter case depends also on the type of material used, recyclable and not toxic, that inevitably is reflected in the selection of the right supplier [35]. Indeed, at BoL, to enable the reverse flow of resources, the design and the procurement functions should be aligned with the other stakeholders' objectives, and in addition the decisions taken should be also coherent with the environmental regulations proposed by the governments and should encounter the relevant standards, such as the ISO [36]. Among the product features, also product dimensions should be designed to be aligned not only with customers' requirements, but also with logistics and transportation requirements, in order to reduce avoidable pollution generation by optimizing the transports [37]. Last, during the production process, the decisions to be taken regard the goal to sustain cleaner production processes. In line with that, the industrial waste generated should be analysed in order to evaluate whether to reuse waste [38] or sell it as a resource to someone else establishing for instance industrial symbiosis [39]. Wrapping up, at product BoL, product features should be thought to encounter all the next stages emerging requirements. Therefore, it is of relevant importance to ensure product high quality levels by adding appropriate services to support its maintenance after selling

and to design appropriate spare parts to maximise the extension of the product life cycle. In addition, further efforts must be done in designing a product to enable its future refurbishment and its possible re-design, to allow the company to be always aligned with market needs.

To conclude, having analysed each stage of the product life cycle and having determined the most relevant decisions to be taken, it was possible to individualize the main criticalities related to information management according to the extant scientific literature. Indeed, due to these criticalities the decision processes is limited and this overall complex mechanism to ensure circular product life cycle is constrained. The criticalities emerged are: technical, managerial and semantic.

- **Technical criticality:** data and information integration inter- and intra- firms' information systems [24] along the product life cycle [40].
Advanced technologies might support product and material traceability such as the blockchain [37], and also more traditional information systems should be designed to enable systems integration, for instance, the Enterprise Resource Planning (ERP) might be used to support product recovery [41]. In both of the cases, the integration with other systems is important to efficiently use them.
- **Managerial criticality:** data and information sharing inter- and intra- firms [42][39].
Indeed, information sharing inter firms requires that the entire company would be involved to efficiently embrace this new paradigm. In particular, the top management should promote a common direction, towards circularity, and all the other functions should be aligned with that. For instance, procurement should select the right materials in alignment with the business finance department budgetary constraints and the design department requests, which depend on marketing analysis. Moreover, in order to pursue the right direction, external industrial companies, affecting the business, need to be aligned with the company under analysis. For instance, the suppliers selected need to embrace common values of the supplied one.
- **Semantic criticality:** there is a lack of data and information standardization, which is reflected in the need to develop a common language sharable among different entities [43] [39]. This is a fundamental aspect to be considered in order to ensure efficient information sharing.

Some attempts to cover these criticalities, and structure these data, have been proposed by scholars. For instance, the ontology thought to develop an eco-industrial parks platform in order to manage input and output flows of resources through a standard language [44], and the knowledge management model for Product-Service System enabling to reuse and share explicit and tacit knowledge through knowledge standardization [45]. Nevertheless, for the discrete industry very few has been done [46] and further studies are required to be developed to encounter all the circular economy principles in discrete manufacturing companies, being heterogeneous the information and data regarding the discrete industry [43].

4 Results and Discussion: Data Classification Model for Circular Product Life Cycle Management

Based on the results of the literature review, summarized in Table 1, it is possible to highlight the main decisions to be taken and to derive the major data required to support the decision-making process of manufacturers in charge of the design and production process, thus involved at BoL of the product life cycle. This enabled to put the basis to cover the information management criticalities, especially regarding the managerial and semantic ones.

In line with the information management criticalities, the first result emerged from the extant scientific literature is related to the heterogeneity of the clusters of stakeholders involved along the product life cycle. These are not only internal to the company, such as the company's functions, but also external, as governments, customers and suppliers (see Fig.1).

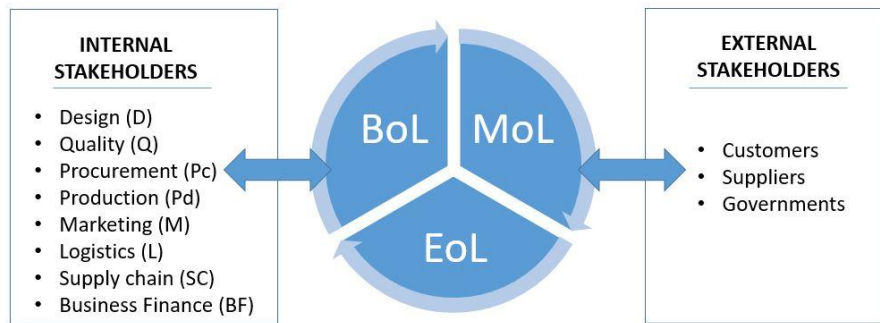


Fig. 1 Internal and external stakeholders impacting manufacturers decision process along the product life cycle

In particular, on the basis of what emerged from the review, the internal stakeholders involved in the circular product life cycle management are aligned with those already reported in the literature of product life cycle [47] but with a different shadow. In the present work, internal stakeholders are defined as follows:

- The *design department* is in charge of engineering and designing the product by defining product characteristics aligned with circular economy principles. This department is affected by customers' needs and requirements, economic constraints and governments regulations. Indeed, it must be highly aligned with marketing department and should direct the choices of procurement department.
- The *quality department* is in charge of monitoring the quality of materials and products, either just produced or turned back. It is influenced by the production, the feedbacks from the customers and thus, the data gathered by the marketing department.

- The *procurement department* is in charge of selecting appropriate suppliers and the related adequate materials or components in line with circular economy principles. This department is influenced by the design department and the business finance since it must be aligned with what defined by designers and its budget is constraints by economic objectives.
- The *production department* is in charge of producing the product by respecting environmental standards and circular economy principles. This department is influenced by the design and the governments.
- The *marketing department* is in charge of taking care of customers' expectations and demand. This department works highly close to the market and thus, it must be aligned with what is requested by customers and has to boost they requests in terms of “circular” products.
- The *logistics department* is in charge of enabling all the transportations required to reach the customers and, also all the transportations required to enable the reverse flow of products and other resources.
- The *supply chain department* is in charge of establishing the right relationships with external companies. In particular, in the present work, this department is responsible for not only manage the relationships with the actors involved in the traditional supply chain but also establishing the right partnerships with other external actors in order to enable the exchange of waste, by-products and other resources.
- The *business finance department* is in charge of establishing the economic objectives and constraints to be set for all the other company’s functions.

On the other side, in the present work, it is supposed to not have intermediaries, indeed the main external stakeholders are three and, are defined as follows:

- The *consumers* are the final end-users of the product. They are responsible to do not dispose the product once it has no more value according to them and to enable its reverse flow.
- The *suppliers* are those which provide the producer with the right materials and components to enable product development and ensure product circularity.
- The *governments* which dictate the most rigid rules and regulations to be respected. These are more than one since foreign markets might follow different regulations under different governments.

Considering the objective of enabling circular product life cycle management, both internal and external stakeholders emerged to be important to determine all the information required at BoL. Indeed, this enables to take into account all the implications, criticalities and requirements that might be encountered along the other stages of the product life cycle that could limit the closing of the resources loop.

In Table 1 are reported the most relevant decisions, emerged from the scientific literature, to be undertaken at BoL by the product producer thus, by its internal stakeholders. As visible, these decisions are taken internally by the different functions, which are influenced one another and need to be able to balance their choices due to the not always aligned objectives. Indeed, their objectives and choices are also affected by external

stakeholders' behaviors, objectives, and decisions that are involved along the product life cycle. Therefore, the data classification model reported in Table 1 enables to envisage the decisions which, if not taken at the BoL, would arise subsequently in the next phases by limiting product circularity. Indeed, this enables to prevent the product to not be able to meet circular economy principles and thus, it allows to limit the product disposal whenever the product itself or its components are still valuable if appropriately managed. Moreover, this model is a preliminary attempt to face at least the semantic and the managerial criticalities that emerged from the extant literature.

Relying on what has been envisioned in the literature, each decisions to be made requires specific data and these data are reported in Table 1 too. In the present work, data collection concerns only product and part-product data required along each stage of the life cycle, with the ultimate goal to extend the product lifetime starting from the product BoL and thus, to facilitate “circular product life cycle management”.

Table 1 Data collection to support the decision-making process enabling a circular product life cycle management

| Product life cycle stage | Decisions | Data | Internal stakeholders | External stakeholders |
|--------------------------|---|--|-----------------------|------------------------|
| BoL | Definition of product features | -Materials -Dimensions -Requirements and governments standards | D, Pd, M | Customers, Governments |
| | Definition of industrial waste management practices and possible partners | -Type of scrap generated -Quantity of scrap generated -Type of by-products generated -Quantity of by-products generated | Pd, SC | Governments |
| | Definition of product functionalities | -Customer needs and requirements | D, M | Customers |
| | Definition of circular product requirements | -Parts product to be disassembled -Recyclable material -Non-toxic material -Environmental governments requirement | D | Customers, Government |
| | Sustainable supplier selection | -Material recyclability -Environmental standards of the supplier | Pc | Suppliers |
| | Definition of the final market | -Customers quantity demand -Environmental ISO | L, Pd, M | Customers |

| | | | | |
|-----|--|---|-----------------|----------------------|
| | Definition of standards to be adopted | | | Governments |
| | Definition of economic constraints | -Material costs -Production costs -Marketing costs | BF, M, Pc | Customers, Suppliers |
| MoL | Definition of guidelines to help end-users to circularly manage products | -Part components description -Material compositions | M | Customers |
| | Definition of unsold products management practices | -Quantity of unsold products -Seasonality of unsold products | M | Customers |
| | Definition of after-sales services | -Spare parts characteristics -Repair activities description | M,D | Customers |
| EoL | Definition of end-of-life practice | -Quantity of products brought back -Quality of products brought back -Parts to be disassembled -Parts to be substituted -Parts to be remanufactured -Parts to be disposed -Costs of the different scenarios | L, Q, Pc, BF | Customers |

5 Conclusions and Limitations

The present work aims to put the basis to streamline information management to enable circular product life cycle management. In particular, the paper identifies the major criticalities related to information management under a circular economy perspective and analyses the main decisions to be taken during the BoL of product, that emerged to be the most important stage in circular product life cycle management. This analysis enabled the development of a data classification model that has been designed to create the ground to face the criticalities that emerged from this review, especially the semantic and the managerial ones. Therefore, it represents the starting point to define a common language, at least exploitable within firm's boundaries, with the final goal to extend the model to finally standardize product data to ease circular product life cycle management.

Indeed, the main results of this contribution are the development of this data classification model and the identification of the role of the stakeholders involved along circular product life cycle management. The data reported in the model are the minimum

requirements to be considered while dealing with circular product life cycle management. This is the first attempt that lays the foundation for a holistic data classification model, aiming to face the major criticalities that emerged from the review (e.g. technical, managerial and semantic) and thus, aiming to support the manufacturers complex decision process affected by heterogeneous stakeholders. Therefore, it has been highlighted that different company's functions necessitate to cooperate to enable the product final reintroduction in a new cycle and, many external stakeholders influence the circularity of the product. More in detail, design, quality, procurement, production, marketing, logistics, supply chain and business finance represent the most relevant functions covering a prominent position in the circular product life cycle management; while the most relevant external stakeholders are the customers, the suppliers and the governments. This requires to horizontally and vertically align the decision process in manufacturing companies and to include appropriate tools and to standardize information to enable the interoperability and the streamlining of the information flows also outside companies' boundaries.

In terms of limitations of the contribution, the focus of the present work is on product data, while the context in which manufacturers necessitate to operate is broader. This implies on one side to consider, for future researches, also process data and other sources of data thus, to take into account all the stakeholders along the entire supply chain, also externally to the firms, such as intermediaries between producers and final consumers. On the other side, it is required to include in future researches also other implications impacting the circular product life cycle decision process, such as the emissions generated to refurbish a product or to recycle the material, and the localization of the suppliers/retailers/consumers.

Moreover, to furtherly validate this primary result, concerning product data classification, this model should be applied on an empirical case and a performance indicator should be developed to demonstrate the benefits of the model.

Regarding future researches, first, being CE a driver for sustainable development, it must not be neglected to cover the three sustainable pillars (i.e. environmental, social and economic). Indeed, data sources and data requirements must be furtherly analyzed in light of this model to include all the pillars. In the reference literature, based on the above mentioned keywords, few contributions have investigated in detail economic issues and thus, further researches should be developed.

Second, as emerged from the scientific literature, one of the information management criticalities is the managerial one and, the decisions that the producers have to take might regard different levels within the organization such as strategic, tactical and operational. Indeed, in future researches, in order to provide a concrete tool exploitable by manufacturers, the sources of data must be analyzed looking at these three hierarchical levels.

Last, another criticality emerged is the technical one thus, more technologically oriented researches should be developed in order to identify what are the potentialities of traditional and more advanced technologies to support circular product life cycle management in light of this model. It is worth's to underline that an extensive literature has been already developed about Product Life Cycle Management systems, nevertheless, other traditional or industry 4.0 related technologies and software might be studied in

light of these new circular requirements. Out of the possibilities, enterprise resource planning (ERP) and customer relationship management (CRM) systems might be integrated to streamline the information flows and facilitate resources loops. In addition, simulation and sensorized systems, if appropriately integrated, could even further support decision process relying on appropriate data gathering.

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