Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 105 (2022) 851–858

www.elsevier.com/locate/procedia

29th CIRP Life Cycle Engineering Conference

Circular Economy: A Product Life Cycle Perspective on Engineering and Manufacturing Practices

Maya Reslan[a], Noah Last[b], Nehika Mathur[a], KC Morris[a], Vincenzo Ferrero*[a]

[a]*National Institute of Standards and Technology, 100 Bureau Dr, Gaithersburg, MD 20899, USA*
[b]*Georgetown University, 3700 O St NW, Washington, DC 20057, USA*

* Corresponding author. *E-mail address:* Vincenzo.Ferrero@nist.gov

Abstract

Realization of a *Circular Economy* is paramount to solving global challenges in resource scarcity, sustainable manufacturing, and supply chain uncertainty. A *Circular Economy* (CE) is an economic system hallmarked by linearity reduction, decoupling of economic growth and resource depletion, and favoring regenerative models that consider sustainability. Growing support for a CE is leading to the proliferation of new economic terms, standards, and research to meet the different goals of CE. However, gaps exist in the formalization of these CE terms, frameworks, and research contributions. This paper provides a system-level context for a CE from the perspective of manufacturing in the product life cycle. We do this using the standard process modeling representation IDEF∅. The main contribution of this work is to provide the general context for a CE system by examining each CE activity involved in the creation of a product, reviewing the current literature, identifying current CE standards status and directions, and discussing CE concepts present in current business practices. This work will act as a reference for identifying gaps in research and standards development for integration of CE in manufacturing practices. Through this work, we identified two opportunities for furthering CE progress: metrics for measuring CE success and a standard CE framework with term definitions.

Peer-review under responsibility of the scientific committee of the 29th CIRP Life Cycle Engineering Conference.

Keywords: Circular Economy; Re-manufacturing; Recycling; IDEF∅; Waste Hierarchy; Sustainability; Process Flow; Reuse; Production; Standards; Environment; Product Life Cycle; Sustainable Manufacturing; Manufacturing Standards; Digitization; Manufacturing Reference Model;

1. Introduction

Manufacturing has significant impacts on the environment and the way humans consume natural resources. As society has become more advanced in its ability to produce goods, so too have societal pressures to control the impacts of the production processes. Classically, regulations on environmental and societal impacts have been implemented in a reactive approaches toward limiting the negative impacts of manufacturing. More recently, producers have sought more proactive ways to limit impacts by anticipating them during planning and production phases; however, regulation has been largely limited to explicitly detrimental effects of particular practices. Only in the last few decades has the impact of consumption at large—the sum total of our economic systems—begun to emerge. In 1988, the paper *The Economics of Natural Resources* introduced the concept of a circular economy (CE) to manage, mitigate, and measure the sum total of the classic linear economic systems that exist today [30]. A *Circular Economy* is an economic system that reduces linearity of the traditional economic system, decouples economic growth from resource depletion, and favors the use of regenerative processes to maintain resource quality and increase longevity in the economic system [29].

While CE is not a new idea, momentum around the concept has surged in recent years. In 2020, the European commission adopted the *Circular Economy Action Plan* (CEAP), which focuses on normalizing sustainable products in the European Union (EU), better managing high resource sectors, reducing waste, and contributing to global CE standards [17]. Regarding standards development, the British Standards Institution (BSI) introduced the first CE-based standard, BS 8001, in 2017 [11]. Since then, the International Organization for Standardisation (ISO), ASTM-International, and the European Committee for Standardization (CEN), as well as other standards development organizations, have established efforts to contribute and adapt standards to address CE principles.

2212-8271 © 2022 The Authors. Published by Elsevier B.V.

Peer-review under responsibility of the scientific committee of the 29th CIRP Life Cycle Engineering Conference.
10.1016/j.procir.2022.02.141

As demonstrated by global interest in defining and standardizing *what* CE is, we look to continue to solidify the context of CE. Common contexts and definitions enable enterprises, standards committees, and government entities to cooperate together in the move towards global sustainability and increasing the value proposition of adopting a CE. Fundamental to this transformation, we propose a systems perspective towards production and resource use. This paper examines the activities involved in the typical product development life cycle from an engineering and manufacturing perspective and identifies areas where changes to those practices are needed to inform decision making and limit the flow of materials out of the economy. In particular, we examine the phases of a product life cycle, with a focus on opportunities for system-level optimization through understanding of the material and information flows across activities within a CE. Our analysis highlights the impacts of circularity on the activities in the various phases of life cycle engineering.

In this paper, we introduce a top-level model for a manufacturing-based CE that describes the high level activities in the system and the flow of materials and information between the activities. Furthermore, we use this model as context to highlight the current state-of-the-art in realizing a CE culture in literature, industry, and standards development for each top-level CE activity. The goals of this paper are to introduce a preliminary framework for discussing the impact of CE across life cycle phases; review current literature, industry, and standards efforts as they relate to the phases; and identify gaps in the literature, limitations in industry, and opportunities for standards development. In providing this review of CE, we look to inform and frame the discussion around how to best represent higher fidelity lower-level abstractions of each activity presented in the introduced model.

2. Motivations for a Circular Economy

The manufacturing industry, made up of firms that use processes to create products from raw materials and/or components, provided value to the evolution for modern society but also contributes to environmental degradation [8]. Historically, this dichotomy has evolved under the concept of a linear economy where there is a disconnect between new-to-market products and the disposal of obsolete products. Extended producer responsibility (EPR), a policy tool that makes the producer responsible for the environmental impacts of a product throughout its life cycle [20], is one popular strategy for breaking this cycle of production. A growing movement for manufacturers to address the environmental impact on the emissions and waste fronts is evolving as a patchwork of initiatives and cooperative agreements [51]. Comprehensive regulations and standards for implementing a CE in manufacturing are now emerging. Without a holistic approach to CE in manufacturing, end-of-life strategies for products will continue to have problems with implementation, cost competitiveness, rebound effect, and effectiveness [55, 8].

Recent studies and literature reviews reported circular business models (i.e., sustainable business models or green business models) are needed to develop this holistic strategy around implementing a CE [48, 43, 14, 8]. There is also a strong need for measurement tools that assess the effects of these circular business models, from improving a manufacturer's bottom line to furthering economic, social, and environmental sustainability goals [8, 18, 31]. The manufacturing-based CE model proposed in our work can act as a high-level model of recommended practices to inform a circular business model. As Rosa et al. described, a circular business model maintains a product's value through, for example, lowering the manufacturer's dependence on virgin materials, shifting from non-renewable to renewable forms of energy, adopting more sustainable production practices, and greening the entire value chain [43].

3. Model-Based Representation of a Circular Economy

Here we present a reference model for a manufacturing-based CE using the Integrated Definition Method (IDEF∅) to frame the current efforts in the general CE life cycle. The IDEF standard is chosen for its previous applications in manufacturing system integration, environmental and economic cost modeling, and for its quick visual reference representation of information flows[13, 54, 28, 59]. IDEF comprises a family of modeling languages commonly used to represent an enterprise-level system [59]. IDEF is derived from Structured Analysis and Design Technique (SADT) [22, 44]. Specifically, IDEF∅ is a standard method of function and process modeling. The IDEF∅ method models the activities [1], inputs [2], outputs [3], mechanisms [4], and controls [5] of an organization or system [37]. The standard IDEF∅ schema is shown in figure 1.

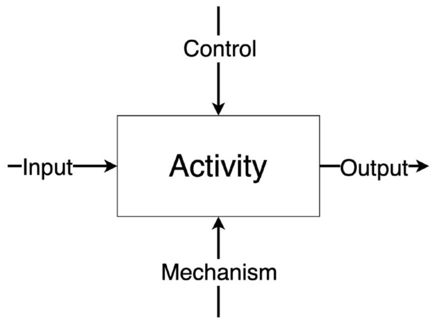

Fig. 1. IDEF∅ model schema.

Figure 2 shows the top-level manufacturing-based CE IDEF∅ model. The manufacturing-based CE model builds on the Reference Architecture for Smart Manufacturing developed at NIST [6].

[1] *Activity* is a modifying function being modeling within the IDEF∅ model.
[2] *Input* is a flow that is being modified by the activity.
[3] *Output* is the resulting flow acted upon by the activity.
[4] *Mechanism* is the means and tools employed to complete the activity.
[5] *Control* is the condition required to ensure the correct output is generated.

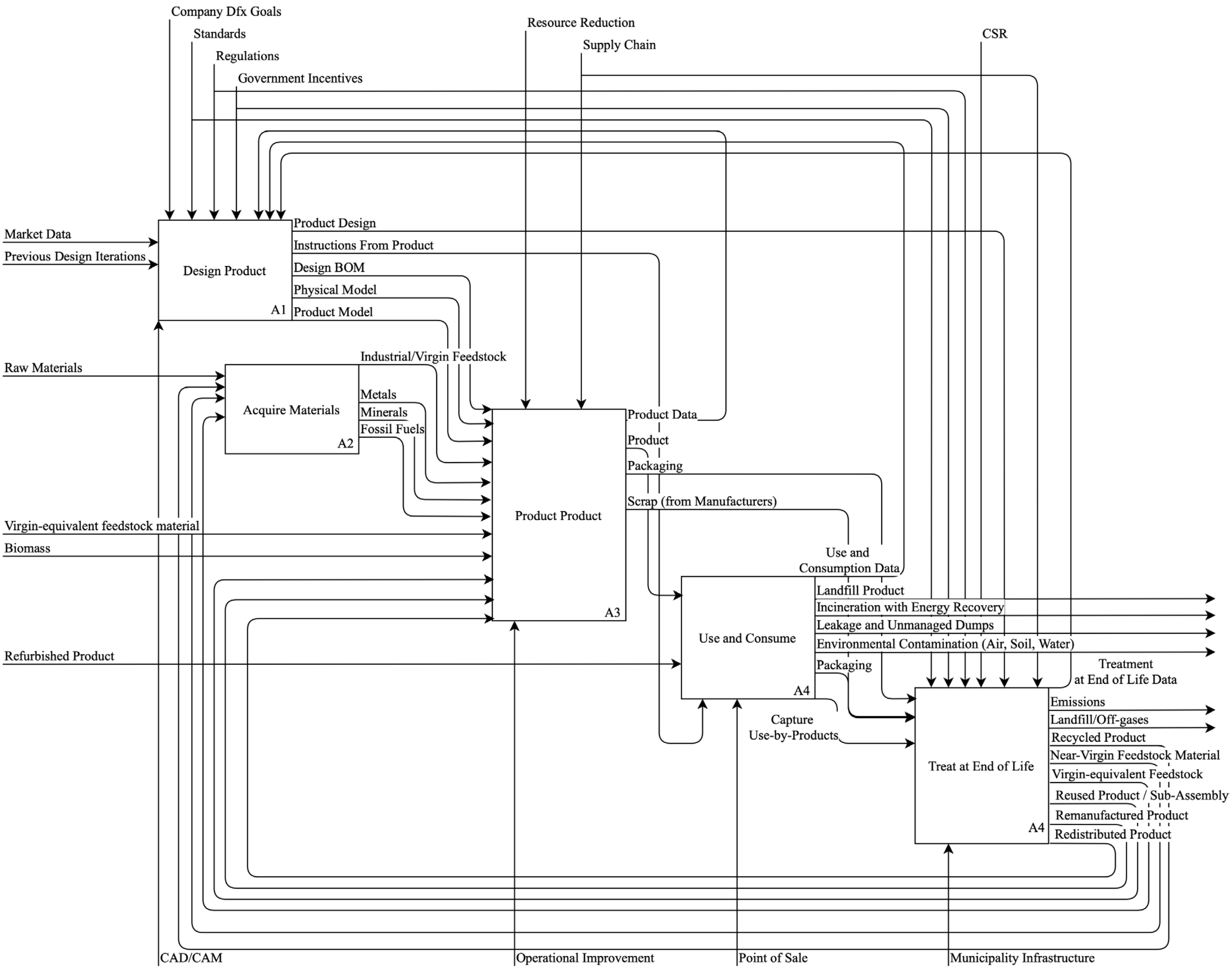

Fig. 2. The proposed manufacturing-based *Circular Economy* IDEF∅ A0 top-level model.

The following subsections review current literature for each A-# model within the *CE* IDEF∅ model, followed by a section on standard movements. Five sub-functions have been identified in the IDEF∅ A0 model, Production in a CE. The top-level A-n models are Design Product, Acquire Materials, Produce Product, Use and Consume, and Treat at End-of-Life (EoL). The function of Acquire Materials (A2) is to transform source materials (raw or recycled) into industry feedstock to create a supply for function A3, Produce Product. A3 Produce Product represents product component manufacturing, product assembly and distribution of a ready product. A4, the Use and Consume activity, relates to the period when a consumer possesses the product. Once the product has fulfilled its primary use and/or the customer chooses to discard it, the product undergoes A5 Treat at End-of-Life. Unlike a traditional linear economy (take, make, dispose), a CE facilitates the reuse, remanufacturing, recycling, and energy recovery of end-of-life products as opposed to traditional waste processes. It is important to note that activity A1 Design Product dictates the degree to which CE can be implemented. Further details on each product life cycle phase in a CE are given below.

3.1. A1: Design Product

Product design is the initial activity toward bringing a product to market. In this activity, product design teams evaluate current product gaps, market trends, and consumer behavior to best identify problems that an enterprise can solve with new or redesigned products [50]. In this activity, a team establishes the needs of stakeholders, generates engineering specifications, and compiles a final product design that best meets these identified needs and specifications [50]. In modern product design, *Design-for-X (DfX)* is a concept in which stakeholder requirements encourage deliberate special design consideration. Global product markets, climate change mitigation, company initiatives, and government mandates inspire *DfX* considerations, such as Design for the Environment, Design for Manufacturing, Design for Assembly, and now, *Design for a Circular Economy*.

To successfully consider *Design for a Circular Economy*, product design teams must know about domain drivers from other life cycle phases such as material vendors, manufacturing engineers, production facilitators, waste treatment plants, and secondary markets. To fully realize a CE at the product design level, information on each of these life cycle phases must be actively propagated back to design teams, as shown in figure 2. The following is a review of studies on executing product design in a *CE*.

Over the last decade, product design considerations have become a hot topic in research on CE. In 2015, van den Berg and Bakker defined the product design framework for a CE [53]. The aim of this work was to answer the question "What is circular product design and how can it be applied in the design field?" The authors redefine the terms future proof, disassembly, maintenance, remake, and recycle in the context of product design. From here, a circular product design framework was developed to show how to best meet the newly defined circularity terms. In other work, Bocken et al. looked at the transition from a linear to circular business model [9]. Here the authors define new terms such as slowing, closing, and narrowing recourse loops. Using these new terms, the authors introduce new *DfX* terms around circularity and discuss six business model strategies toward slowing loops and closing loops. These works mark the beginning of defining new terms for product design within a CE context.

Recent research has introduced and defined new terms such as product lifetime, resource leakage, and recovery horizon [21]. New research is moving from term definitions into quantifying indicators to measuring product performance in a CE [12]. Finally, Bakker et al. called for a special issue in 2021 to understand and manage product lifetimes in support of a CE [5].

3.2. A2: Acquire Materials

Manufacturing entails the transformation of raw materials into a final product based on market requirements. Subsequent to, and based on a product's design, the next phase in a product's life cycle involves acquiring material feedstock to produce the given product (See figure 2).

Raw material is first extracted from natural resources through several physical and/or chemical processes. The extracted material undergoes further processing to transform it into industrial feedstock with specifications based on the functionality of the product and its design. It should be noted that the materials acquisition phase marks the beginning of the supply chain and comprises vendors who often source feedstock from a complex, global network to manufacture a given product. Therefore, other considerations during the materials acquisition phase include cost, transportation, labor, equipment and machinery, and of course regulations and standards.

Past challenges related to material acquisition had to do primarily with choosing the right material(s) at the right cost for a given product or component. Material selection plays a key role in ensuring product functionality and quality, and therefore there are several well-established standards (e.g., ISO and ASTM) and frameworks to guide product developers [2, 16, 19, 58]. These standards also ensure user and/or environmental safety by limiting or eliminating hazardous substances from the product or specifying safe handling methods through the use of product labels and/ or markings [49, 3].

3.3. A3: Produce Product

A manufacturing process is a method of determining the connection, coordination, and execution of production steps required to create a product. When a corporation starts manufacturing a product, factors including consumer demand, the production technology used to create the product, and the company's available resources will all influence the process. Each method is unique and has its own set of benefits. Manufacturing in batches, for example, might be done in large quantities, in a continuous stream of goods, or in smaller batches to satisfy consumer demand and reduce waste.

After the material is extracted, materials are processed and manufactured in different ways depending on the industry. Once the product is designed, it can be manufactured, assembled, and distributed. To ensure smooth production, the materials should be managed and the tasks scheduled. This involves defining the production process to create production schedules and regulating the flow of materials into and out of the manufacturing plant, as well as scheduling, controlling, and executing production processes and allocating human and machine resources to production operations and, finally, developing an implementation plan.

Factories harm the environment when they emit pollutants into the air, dispose of toxic waste, or contaminate water. They also can be significant polluters when it comes to greenhouse gas emissions—industry emissions account for 23 % of the US-based emissions that contribute to global climate change [52]. Despite this unfavorable statistic, technological advancements have provided facilities with a variety of options for decarbonizing manufacturing processes [42, 56].

The Industrial Revolution fundamentally changed society's relationship with the environment by increasing the use of natural resources and the rate at which new goods and processes are developed [57]. This is illustrated by manufacturing's depletion of resources, disruption of natural ecosystems, and pollution from undesired byproducts of the manufacturing process and abandoned items at the end of their useful life. Concern for the environment has recently prompted the manufacturing industry to take the lead on new methods and designing recyclable products.

A CE is increasingly being viewed as a potential solution to a number of problems, including waste creation, resource scarcity, and long-term economic advantages. The idea of circularity, on the other hand, is not new. In the past, certain conditions and motives have sparked circularity-related concepts through actions such as reuse, re-manufacturing, and recycling [32]. In conclusion, governments, companies, and communities all over the globe are working to adapt to issues such as resource scarcity, environmental damage, or economic advantages, or combinations of these. However, a large portion of these efforts lack a systematic approach, making the CE method essential.

3.4. A4: Use and Consume

Once the product is manufactured, it is distributed for use and consumption by the masses. This phase of the product's life cycle involves consumer ownership of the product and is challenging to regulate. While most manufacturers provide instructions on effective and safe usage of a product, it remains difficult to monitor how individual consumers use the products. Thus, products could inevitably be used in ways that are inefficient and/or unsafe. The consumer may decide to discard the product before it reaches its End-of-Life (EoL). In such a scenario, the product may get passed on to another consumer, simply be disposed of, or end up in storage.

The notion of CE makes it imperative for both consumers and manufacturers to minimize material losses before, during, and after a product's primary use. Implementing policies that enhance efficient and safe use, and providing consumers with the know-how to manage products in the long term (product labels, regulations, standards), could lead to widespread adoption of CE among consumers.

A recent study by Boyer et al. revealed that a product label with a CE score impacts the consumer's perception of that product. Consumers do indeed prefer circular products and are willing to pay more for them (for products with up to 50 percent recirculated content) [10]. Similarly, Mak and Terryn propose consumers be part of the CE movement by promoting product repair and sharing products through service models [34]. Product labelling to promote CE can lead to behavioral changes in both the product's producers and consumers. Eco-labelling encourages manufacturers to implement more sustainable practices, while encouraging consumers to opt for products with lower environmental burdens. They also allow effective communication that promotes less waste by replacing the notion of EoL with material recovery [36].

3.5. A5: Treat at End-of-Life

Products are made of both the actual materials used to make them and embedded resources (i.e., resources used to manufacture the product, like energy, resources such as water, expertise, and labor). In the traditional linear economy, these products are simply disposed of into landfills, resulting in the loss of valuable resources. A more holistic approach like CE diverts these 'resources' away from the landfill, thus reducing the overall environmental burden of the product.

Material recovery or closing material loops is an extremely complex problem, and the initial product design plays a crucial role in overall product recovery [40]. Recovering products at their EoL entails collecting, sorting and processing. Most

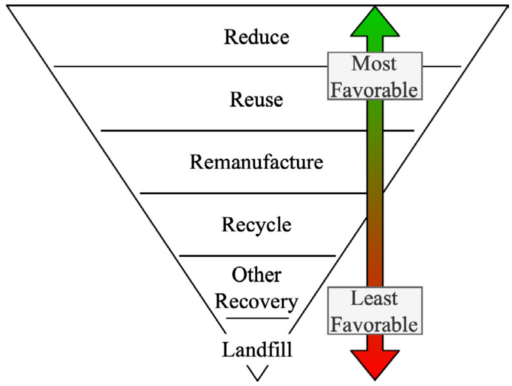

Fig. 3. The waste hierarchy (adapted from the EU Waste Framework Directive 2008/98/EC.

products are a combination of several components, and subassemblies fabricated using different materials and effective disassembly strategies may help isolate material streams and prevent cross contamination. Ideally, treating products at their EoL should follow the principle of waste hierarchy (See figure 3), i.e., disassembling for direct reuse, re-manufacturing, and recycling, i.e., the 3Rs. The remainder of the product would be incinerated for energy recovery, followed by landfilling [41].

The use of the principle of waste hierarchy in the context of specific case studies are found on reviewing the literature. The principle of waste hierarchy to promote CE has been explored relative to food waste management, paper recycling opposed to incineration or landfilling, reusing electric vehicle batteries for stationary energy storage purposes and others [38, 15, 46, 15, 41, 35]. In this regards, research exploring the development of EoL decision-making tools continues [39, 7, 1]. As mentioned earlier, implementing effective EoL treatment is fraught with challenges related to infrastructure and technology, behavior, and a lack of effective frameworks and standards. There is a clear gap with respect to standards pertaining to EoL material recovery that considers the waste hierarchy. There is a need to clarify EoL treatment and recovery terminology, besides developing standards specifically for recovered material so that it may in turn be commercially viable.

4. Standards Representation and Discussion

While the concept of CE is rapidly being adopted by governments and multinational organizations, comprehensive standards are needed to fully realize the concepts that are being formulated and build on existing work towards more sustainable manufacturing. As shown in Figure 4, three main categories of standards will support the CE from differing perspectives. Shared goals (bottom left) inform and set direction for the definition of the other types of standards and include work such as the United Nation's Sustainable Development goals[47], Green House Gas (GHG) protocols[24], and the Sustainability Standards Accounting Board (SASB)[45], among others. Management standards specify good practices for rigorously and thoroughly managing a manufacturing organization to improve sustainable performance and include standards, such as the ISO management standards [25] which have been shown to improve sustainability outcomes consistently across organizations and industries and CEN-CENELEC Joint Technical Committee 10[23] addressing material efficiency in energy-related products. Finally, measurement standards establish rigor in implementing continuous improvement processes, material quality and performance requirements, demonstrating achieved results and are necessary for responding to the other categories. Measurement standards include the wide-breadth of standards specific to materials, as well as foundational standards supporting process modeling and continuous improvement such as those addressed by ASTM International E60 [4, 27]. The introduction of new manufacturing technologies often referred to as Smart Manufacturing or Industry 4.0 allows for tighter integration of the management and measurement aspects[33].

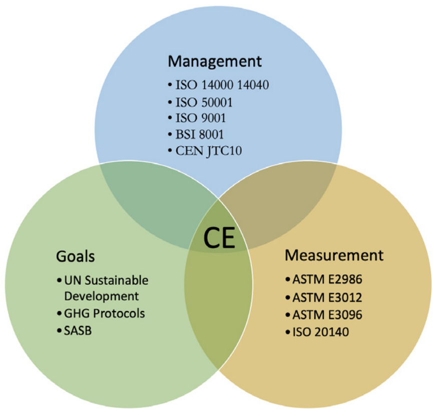

Fig. 4. Categories of standards supporting a Circular Economy

The complete set of standards needed to support the CE will build on those that span the product life cycle phases, the supply chain, and the gamut of industries, including material producers; these standards will require the range of perspectives that these categories reflect. Newly emerging standards for addressing CE specifically build on contributions from the academic literature that focus on defining new terms, businesses model strategies, and frameworks for CE, as well as existing standards, including those highlighted to foster new pathways for material flows and efficiency. The ISO 323 Technical Committee on CE is developing a new suite of standards to address the foundations specific to CE[26]. Most fundamental will be standards for terminology and principles to help guide further integration efforts.

Future standards are expected across the range of standards development organizations to facilitate the transfer of information between activities represented in the CE framework for the product life cycle that is proposed here. For example, information representations about recirculated materials and their properties can be standardized and shared with design and production CE activities. By facilitating standard information flows, design engineers can make informed decisions using uncertainty quantification around material quality and availability. Similarly, manufacturers can implement develop alternative production plans based on uncertain material qualities and supply chain resilience.

In the context of CE literature, new challenges identified around measuring CE success. Future research can build on framework and term definitions to introduce novel metrics for measuring. In this emerging research space, researchers can build on (LCA) tools to quantify early adoption of CE concepts as they affect product and manufacturing sustainability. Moving forward, new CE-centric metrics will be needed to measure waste mitigation, supply chain resilience, feedstock quality and quality uncertainty, product circularity, and dynamic changes in manufacturing processes. Such CE metrics will be useful for simulating supply chain and production planning and can be input for digital twins capable of adapting systems to perturbations in recirculated material properties during manufacturing, production scheduling, post-use recycling, re-circulation, and product design.

5. Conclusion

In this paper we introduce a manufacturing-based CE function and process model to describe the information and material flows that may be present in a CE product life cycle system. This CE model provides the needed context for a ”whole” picture view of a CE in practice from the manufacturing-centric viewpoint. We describe each life cycle phase as an activity and provide a brief review of current research contributions on that activity. We also review CE in industry and CE-specific standards. In presenting the CE model and subsequent literature review, we assert a need to align existing standards to mature CE frameworks and term definitions. Also noted are challenges and needs for novel research in CE measurement and definitions of success.Creating such metrics can promote research and development on digital twins to address current uncertainties in a CE, namely in recirculated feed stock material properties, product scheduling, and circularity grading.

Future work will further develop models of CE and CE processes, expanding on the sub-activities to identify the implications of CE in the existing practices, research opportunities, and standards. Case studies will be used to validate the model and further contribute progress and context on each life cycle phase within a CE.

References

[1] Alamerew, Y.A., Brissaud, D., 2019. Circular economy assessment tool for end of life product recovery strategies. Journal of Remanufacturing 9, 169–185. doi:10.1007/s13243-018-0064-8.

[2] Ashby, M., 1999. Materials selection in mechanical design,‖ Butterworth. Heinemann, Burlington.

[3] Ashby, M., Brechet, Y., Cebon, D., Salvo, L., 2004. Selection strategies for materials and processes. Materials & Design 25, 51–67.

[4] ASTM-International, . Subcommittee E60.13 : Published standards under E60.13 jurisdiction. URL: https://www.astm.org/COMMIT/SUBCOMMIT/E6013.htm.

[5] Bakker, C.A., Mugge, R., Boks, C., Oguchi, M., 2021. Understanding and managing product lifetimes in support of a circular economy. doi:10.1016/j.jclepro.2020.123764.

[6] Barkmeyer, E.J., Wallace, E.K., 2016. Reference Architecture for Smart Manufacturing Part 1: Functional Models. Technical Report. National Institute of Standards and Technology. Gaithersburg, MD. URL: https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.300-1.pdf, doi:10.6028/NIST.AMS.300-1.

[7] Bentaha, M.L., Voisin, A., Marangé, P., 2020. A decision tool for disassembly process planning under end-of-life product quality. International Journal of Production Economics 219, 386–401. URL: https://doi.org/10.1016/j.ijpe.2019.07.015, doi:10.1016/j.ijpe.2019.07.015.

[8] Bjørnbet, M.M., Skaar, C., Fet, A.M., Schulte, K.Ø., 2021. Circular economy in manufacturing companies: A review of case study literature. Journal of Cleaner Production , 126268.

[9] Bocken, N.M., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering doi:10.1080/21681015.2016.1172124.

[10] Boyer, R.H., Hunka, A.D., Linder, M., Whalen, K.A., Habibi, S., 2021. Product Labels for the Circular Economy: Are Customers Willing to Pay for Circular? Sustainable Production and Consumption 27, 61–71. URL: https://doi.org/10.1016/j.spc.2020.10.010, doi:10.1016/j.spc.2020.10.010.

[11] BSI, 2017. BS 8001:2017 Framework for implementing the principles of the circular economy in organizations – Guide.

[12] Cayzer, S., Griffiths, P., Beghetto, V., 2017. Design of indicators for measuring product performance in the circular economy. International Journal of Sustainable Engineering doi:10.1080/19397038.2017.1333543.

[13] Chen, Z., Huang, L., 2019. Application review of LCA (Life Cycle Assessment) in circular economy: From the perspective of PSS (Product Service System). Procedia CIRP 83, 210–217. URL: https://doi.org/10.1016/j.procir.2019.04.141, doi:10.1016/j.procir.2019.04.141.

[14] Environment, C., Canada, C.C., . Economic study of the Canadian plastic industry, markets and waste : summary report.

[15] Eriksson, M., Strid, I., Hansson, P.A., 2015. Carbon footprint of food waste management options in the waste hierarchy - A Swedish case study. Journal of Cleaner Production 93, 115–125. URL: http://dx.doi.org/10.1016/j.jclepro.2015.01.026, doi:10.1016/j.jclepro.2015.01.026.

[16] Ermolaeva, N.S., Castro, M.B., Kandachar, P.V., 2004. Materials selection for an automotive structure by integrating structural optimization with environmental impact assessment. Materials & Design 25, 689–698.

[17] European Commission, 2020. Circular Economy Action Plan: The European Green Deal. European Commission .

[18] Frishammar, J., Parida, V., 2019. Circular business model transformation: A roadmap for incumbent firms. California Management Review 61. doi:10.1177/0008125618811926.

[19] Giudice, F., La Rosa, G., Risitano, A., 2005. Materials selection in the life-cycle design process: a method to integrate mechanical and environmental performances in optimal choice. Materials & Design 26, 9–20.

[20] Gupt, Y., Sahay, S., 2015. Review of extended producer responsibility: A case study approach. Waste Management and Research 33, 595–611. doi:10.1177/0734242X15592275.

[21] den Hollander, M.C., Bakker, C.A., Hultink, E.J., 2017. Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. Journal of Industrial Ecology doi:10.1111/jiec.12610.

[22] IDEF Logo Integrated DEFinition Methods (IDEF), 2020. IDEFØ – Function Modeling Method – IDEF. Knowledge Based Systems, Inc. .

[23] IEC, . European standards for a circular economy | IEC. Technical Report. URL: https://www.iec.ch/blog/european-standards-circular-economy.

[24] Institute, W.R., World Business Council for Sustainable Development, 2004. GHG Protocol: A Corporate Accounting and Reporting Standard: Revised Edition. Technical Report. Greenhouse Gas Protocol Organization. URL: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.

[25] ISO, a. ISO - Management system standards. Technical Report. URL: https://www.iso.org/management-system-standards.html.

[26] ISO, b. ISO/TC 323 - Circular economy. URL: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/committee/72/03/7203984.html.

[27] ISO, 2019. ISO 20140-1:2019: Automation systems and integration — Evaluating energy efficiency and other factors of manufacturing systems that influence the environment — Part 1: Overview and general principles. Technical Report. URL: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/93/69358.html.

[28] Jun, H.B., Suh, H.W., 2008. A modeling framework for product development process considering its characteristics. IEEE Transactions on Engineering Management 55, 103–119. doi:10.1109/TEM.2007.912808.

[29] Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127, 221–232. doi:10.1016/j.resconrec.2017.09.005.

[30] Kneese, A.V., 1988. The Economics of Natural Resources. Population and Development Review 14, 281–309. URL: 10.2307/2808100, doi:10.2307/2808100. publisher: [Population Council, Wiley].

[31] Kristoffersen, E., Blomsma, F., Mikalef, P., Li, J., 2020. The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. Journal of Business Research 120, 241–261. doi:10.1016/j.jbusres.2020.07.044.

[32] Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. Journal of cleaner production 115, 36–51.

[33] Lu, Y., Morris, K.C., Frechette, S.P., 2016. Current Standards Landscape for Smart Manufacturing Systems. Technical Report. URL: https://www.nist.gov/publications/current-standards-landscape-smart-manufacturing-systems.

[34] Mak, V., Terryn, E., 2020. Circular Economy and Consumer Protection: The Consumer as a Citizen and the Limits of Empowerment Through Consumer Law. Journal of Consumer Policy 43, 227–248. doi:10.1007/s10603-019-09435-y.

[35] Mathur, N., Deng, S., Singh, S., Yih, Y., Sutherland, J.W., 2019. Evaluating the environmental benefits of implementing industrial symbiosis to used electric vehicle batteries. Procedia CIRP 80, 661–666.

[36] Meis-Harris, J., Klemm, C., Kaufman, S., Curtis, J., Borg, K., Bragge, P., 2021. What is the role of eco-labels for a circular economy? A rapid review of the literature. Journal of Cleaner Production 306, 127134. URL: https://doi.org/10.1016/j.jclepro.2021.127134, doi:10.1016/j.jclepro.2021.127134.

[37] NIST, 1993. Integration Definition for Function Modeling (IDEF0).

[38] Papargyropoulou, E., Lozano, R., K. Steinberger, J., Wright, N., Ujang, Z.B., 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. Journal of Cleaner Production 76, 106–115. doi:10.1016/j.jclepro.2014.04.020.

[39] Paterson, D.A., Ijomah, W.L., Windmill, J.F., 2017. End-of-life decision tool with emphasis on remanufacturing. Journal of Cleaner Production 148, 653–664. URL: http://dx.doi.org/10.1016/j.jclepro.2017.02.011, doi:10.1016/j.jclepro.2017.02.011.

[40] Peeters, J.R., Dewulf, K., 2012. Design for end of life: A design methodology for the early stages of an innovation process. Proceedings of the 14th International Conference on Engineering and Product Design Education: Design Education for Future Wellbeing, EPDE 2012 , 185–192.

[41] Richa, K., Babbitt, C.W., Gaustad, G., 2017. Eco-efficiency analysis of a lithium-ion battery waste hierarchy inspired by circular economy. Journal of Industrial Ecology 21, 715–730.

[42] Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S.A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E.D., de la Rue du Can, S., Sisson, B., Williams, M., Katzenberger, J., Burtraw, D., Sethi, G., Ping, H., Danielson, D., Lu, H., Lorber, T., Dinkel, J., Helseth, J., 2020. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. doi:10.1016/j.apenergy.2020.114848.

[43] Rosa, P., Sassanelli, C., Terzi, S., 2019. Towards circular business models: A systematic literature review on classification frameworks and archetypes. Journal of Cleaner Production 236. doi:10.1016/j.jclepro.2019.117696.

[44] Ross, D.T., 1977. Structured Analysis (SA): A Language for Communicating Ideas. IEEE Transactions on Software Engineering doi:10.1109/TSE.1977.229900.
[45] SASB, 2018. Sustainability Accounting Standards Board. Technical Report. URL: https://www.sasb.org/. publication Title: Sustainability Accounting Standards Board.
[46] Schmidt, J.H., Holm, P., Merrild, A., Christensen, P., 2007. Life cycle assessment of the waste hierarchy–a danish case study on waste paper. Waste management 27, 1519–1530.
[47] SDGS, 2015. Transforming our World: The 2030 Agenda for Sustainable Development. Technical Report A/RES/70/1. United Nations. URL: https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981.
[48] Sousa-Zomer, T.T., Magalhães, L., Zancul, E., Cauchick-Miguel, P.A., 2018. Exploring the challenges for circular business implementation in manufacturing companies: An empirical investigation of a pay-per-use service provider. Resources, Conservation and Recycling 135, 3–13. doi:10.1016/j.resconrec.2017.10.033.
[49] Stolt, R., 2012. Designing material standards. Proceedings of International Design Conference, DESIGN DS 70, 1133–1139.
[50] Ullman, D., 2009. The Mechanical Design Process. 4 ed., McGraw-Hill Education.
[51] United States Environmental Protection Agency, 2020. National Recycling Strategy Draft , 1–24URL: https://www.epa.gov/sites/production/files/2020-10/documents/draft{_}national{_}recycling{_}strategy{_}0.pdf.
[52] U.S. EPA, 2021. Inventory of U.S Greenhouse Gas Emissions and Sinks. EPA 430-R-21-005. Environmental Protection Agency .
[53] Van den Berg, M., Bakker, C., 2015. A product design framework for a circular economy, in: PLATE (Product Lifetimes And The Environment) Conference Proceedings.
[54] Waissi, G.R., Demir, M., Humble, J.E., Lev, B., 2015. Automation of strategy using IDEF0 - A proof of concept. Operations Research Perspectives 2, 106–113. URL: http://dx.doi.org/10.1016/j.orp.2015.05.001, doi:10.1016/j.orp.2015.05.001.
[55] Wang, P., Kara, S., Hauschild, M.Z., 2018. Role of manufacturing towards achieving circular economy: The steel case. CIRP Annals 67, 21–24. doi:10.1016/j.cirp.2018.04.049.
[56] Wilson, C., Grubler, A., Bento, N., Healey, S., De Stercke, S., Zimm, C., 2020. Granular technologies to accelerate decarbonization. Science doi:10.1126/science.aaz8060.
[57] Young, P., Byrne, G., Cotterell, M., 1997. Manufacturing and the environment. The international journal of advanced manufacturing technology 13, 488–493.
[58] Zarandi, M.H.F., Mansour, S., Hosseinijou, S.A., Avazbeigi, M., 2011. A material selection methodology and expert system for sustainable product design. The International Journal of Advanced Manufacturing Technology 57, 885–903.
[59] Zhang, H., Haapala, K.R., Vanlue, M.E., Funk, K.H., 2011. Environmental impact and cost assessment of product service systems using IDEFO modeling. Transactions of the North American Manufacturing Research Institution of SME 39, 172–181. doi:10.13140/2.1.1552.4488.