NORDDESIGN CONFERENCE
REYKJAVIK, ICELAND, 12-14 AUGUST 2024

Supporting Design for Circular Economy Using Unit Manufacturing Process Simulation Models

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Abstract: Simulation models are crucial in deploying circular economy (CE) strategies and in circular product design. By highlighting the impact of changes in product life cycle data and behavior on CE performance, simulation models can support decision-making towards Design for CE (DfCE). This paper reviews prior work in this domain and classifies it according to their primary application objectives. Our review suggests that limited work exists on utilizing unit-level manufacturing process simulation models for DfCE. Addressing this gap is vital, as manufacturing decisions can significantly affect a product's CE performance. To this end, this work proposes a methodology for supporting DfCE using unit manufacturing process simulation and demonstrates it on an injection molding process.

Keywords: Circular Economy, Simulation, Manufacturing, Circular Design

1 Introduction

Simulation models can play a critical role in decision-making towards implementing circular economy (CE) strategies (Sassanelli et al., 2020). These simulation models can span from analytical models such as equations and decision flow charts, to more complex model such as discrete-event simulation and agent-based models. For instance, factory simulation models to visualize and improve the product throughput, manufacturing process simulation models, and functional models such as product lifetime prediction, product stress simulation models under different operating environments. CE has been increasingly applied to the manufacturing sector, leading to the development of circular manufacturing (CM) strategies. CM adopts various methods to reduce resource consumption, extend resource lifecycles, close resource loops based on manufacturers' internal and external activities, and to meet stakeholder needs (Acerbi et al., 2021). Concerning the use of simulation models to support design for CE (DfCE), one of the requirements is the use of appropriate indicators that help quantify the current level of CE implementation. Furthermore, there is an increasing recognition that CE indicators need to be considered in combination with sustainability indicators (e.g., from life cycle assessments), as CE and sustainability are not necessarily mutually reinforcing (Jerome et al., 2022). Prior research on simulation-based design has been largely applied towards integrating sustainability considerations at the product design stage through methods such as streamlined life cycle assessments (LCAs) (Bernstein et al., 2020). While product-level CE assessments can be performed using LCAs (Niero and Kalbar, 2019), prior research has also proposed the use of CE indicators for measuring product CE performance (Saidani et al., 2019). Given the fact that several CE and LCA-based indicators can be objectively estimated from product life cycle data, they are well-suited for use in simulation models and can be used as markers for informing decision-making in DfCE.

This paper explores the usage of simulation models for DfCE, with a specific focus on the potential role of unit manufacturing process (UMP) simulation models for supporting decision-making in DfCE. The structure of the rest of the paper is as follows. Section 2 reviews the usage of different simulation models for CE with a focus on identifying models used in circular product design and manufacturing. Next, the resulting literature is classified based on CE-related objectives, and the requirements for using simulation models for DfCE and their shortcomings are analysed. Building on this knowledge, Section 3 showcases the case study of the use of UMP simulation model to support DfCE and Section 4 presents the results and discussions from the case study and Section 5 concludes the articles and discusses future developments.

2 Background

To identify the use of simulation models in DfCE we reviewed the current usage of simulation models in circular product design. We performed a literature search using the Scopus database using the query {"circular economy"} *and* {simulation} *an d* {"product design" *or* "engineering design" *or* "mechanical design"}. A snowballing approach was used to expand our search and include results from prior relevant reviews (Sassanelli et al., 2020). Resulting articles (see

Table 1) were classified based on the primary application objective (emergent from the reviews) of the simulation models. The following paragraphs briefly review the relevant articles obtained in our search.

Most simulation models consist of agent-based, discrete event, and system dynamics methods used mainly for CE-related business applications (Sassanelli et al., 2020). Franco, 2019 investigated the use of system dynamics simulation to analyse various product design and business model strategies for enhancing resource loop efficiency for CE. Their research considered the product design considerations at the start of the product lifecycle and their implications on the product's take-back stage. The goal was to examine the dynamics of different business model strategies aimed at slowing down or closing resource loops. Bosch et al., 2017 created a system dynamics model to estimate the business impacts of adopting a CE framework for a furniture manufacturing company. Their model simulated a change from buy/ sell model to product service system model. Similar usage of system dynamics model was observed by Hao et al., 2012 & Teekasap, 2018. Roci et al., 2022 found multi-method simulation modelling a robust decision-making tool for implementing circular manufacturing systems. Walzberg et al., 2021 used agent-based models to simulate interactions among photovoltaic (PV) owners, installers, recyclers, and manufacturers, exploring factors that maximize PV circularity and modelling various end-of-life schemes and other CE strategies. Similarly, Nishino et al., 2022 used an agent-based simulation to match circular products with customers, considering factors like service life, customer needs, and resource availability, balancing social surplus and circularity. Yazan and Fraccascia, 2020 used an enterprise input-output model along with the agent-based model to simulate the economic benefits from the industrial symbiosis shared by the companies. Other work on the usage of agent-based approach was found in Fraccascia and Yazan, 2018 & Innocenzi et al., 2018.

Simulation-based optimization has also been employed to select appropriate CE strategies. Bal and Badurdeen, 2022 conducted a simulation-based optimization for a lease-and-sell approach, exploring its application for manufacturers considering different end-of-life (EoL) options. The study assessed the lease-and-sell model's feasibility, factors influencing new facility locations, and optimal placement for collection and processing centers. Ameli et al., 2019 developed a multi-objective stochastic optimization model to address the dual challenges of selecting design alternatives and planning end-of-life options for product families by a single producer. Their study correlated total profit, environmental, and social impact with varying recycling rates for these product families.

Low and Ng, 2018 used Monte-Carlo simulation to evaluate the effectiveness of different flexible design strategies while handling uncertainties of remanufacturing systems that stem from market demand, condition at the end-of-life of the parts, geopolitical and socio-economic factors. They showed the application on a laptop remanufacturing by tackling two design variables mainly, remanufacturing location and the capacity size enabling effective implementation of remanufacturing. Similarly, Charnley et al., 2019 utilized discrete event and system dynamics simulations to guide decisions in remanufacturing processes for automotive components.

Process simulation models have been used to select optimum conditions for supporting CE. Matino et al., 2017 modelled process simulation for electrical steelmaking. They evaluated the effect of process modifications such as scrap weight percentage on the selected key performance indicators, including electrical energy consumption, CO_2 consumption, and total slag generated. Reuter and van Schaik, 2015 described the use of a product-centric, simulation-based approach to aid design for recycling (DfR). Their method involved process simulation (using HSC Sim) and design tools to determine material recycling rates and critical designs to establish DfR rules. Hannula et al., 2020 developed a predictive model for an eddy current separator in physical separation processes. They combined this with re-melting and alloying models to form an Aluminium recycling flow sheet. Their approach included resource efficiency and environmental impact assessment through exergy analysis and life cycle assessment simulations. Other relevant research in the usage of process simulation models was by Gaspari et al., 2017 working on reconfigurable simulation models for manufacturing systems.

Pfaff et al., 2018 developed a methodology for analysing material flows with respect to the wider economic system for copper material using combination of macroeconomic simulation model and the substance flow model. Odenbreit and Kozma, 2019 conducted a finite element simulation for dis-assembly and re-assembly of finite structural load bearing elements to make them more modular. Whereas, Aher et al., 2023b analysed the use phase of the pipe flange system to analyse the effects of changing material composition on the lifetime of the system. Table 1 presents an overview of the papers reviewed above, including the type of simulation models used and their corresponding categorization based on the scheme. As shown in Table 1, we classified the use of models related to CE applications based on their primary application objective. Three broad themes emerged from our review, and they are described in further detail below.

Table 1. Overview of the usage of simulation models for CE (C-1: CE-related business strategy, C-2: CE-related lifecycle stages, C-3: CE-related design alternatives)

Author	**Overview**	**Type of Simulation**	**Category**
Charnley et al., 2019	Model to guide decisions related to remanufacturing	Discrete-event, system dynamics	C-2

Reuter and van Schaik, 2015	Product-centric simulation-based approach to recycling	Process simulation	C- 2
Roci et al., 2022	Modelling of circular manufacturing systems as complex adaptive systems for understanding their dynamics	Multi-method	C-1
Hannula et al., 2020	Predictive model for eddy current separator	Process simulation	C-2
Franco, 2019	Simulation of various design and business model strategies	System dynamics	C-1, C-3
Bal and Badurdeen, 2022	Simulation-based optimization for lease and sell approach	Discrete-event	C-1
Nishino et al., 2022	Online platform for connecting circular products with consumers	Agent-based	C-1
Walzberg et al., 2021	Studying the circularity in the photovoltaic supply chains	Agent-based	C-1
Ameli et al., 2019	Modelling the design alternatives and different end-of-life options	Stochastic optimization model	C-3
Matino et al., 2017	Simulation models employed for the quantification of electric energy consumption and environmental impact on electrical steelmaking	Process simulation	C-2
Low and Ng, 2018	Simulating flexible strategies for remanufacturing with uncertainties to improve economic performance	Monte Carlo	C-2
Yazan and Fraccascia, 2020	Modelling the sharing of economic benefits by companies involved in Industrial Symbiosis	Enterprise Input-Output model, Agent-based	C-1
Pfaff et al., 2018	Development of a macroeconomic simulation model to analyze material flows in a wider economic system	Macro-Economic simulation	C-1
Fraccascia and Yazan, 2018	Development of an agent-based model to simulate the operations of Industrial Symbiosis Networks	Agent-based	C-1
Gaspari et al., 2017	Reconfigurable simulation model for remanufacturing systems	Process simulation	C-2
Innocenzi et al., 2018	Simulation of the solvent extraction process for rare earths from fluorescent lamps	Process simulation (Solvent extraction)	C-2
Odenbreit and Kozma, 2019	Modelling to test the suitability of the disassembly/ reassembly process for demountable flooring and beam systems	Finite element modelling	C-2
Bosch et al., 2017	Estimation of potential business impacts of adopting CE principles in a furniture manufacturing company	System dynamics	C-1

Hao et al., 2012	Simulation of various development projects of the coal utilization system	System dynamics	C-1
Teekasap, 2018	Modelling the economic benefits of CE in countries with abundant resources	System dynamics	C-1
Aher et al., 2023b	Model to optimize the system lifetime with changes in selected material	Simulink model	C-3, C-2

Modelling CE-related business strategies (C-1): These simulation models primarily include system dynamics, agent-based, or discrete-event simulation (DES) models, which help simulate the feasibility of a CE strategy. For instance, an agent-based model used to test the feasibility of a product service system (PSS) model. These types of models typically involve modelling the interaction between the different agents (e.g., customers, manufacturers) and their behaviours.

Modelling CE-related lifecycle stages (C-2): These simulation models focus on modelling a product's lifecycle or applications related to a product’s lifecycle stage, for instance, modelling material recycling flow sheets, simulating extraction processes, and modelling different strategies for end-of-life such as remanufacturing and recycling.

Modelling CE-related design alternatives (C-3): These simulations focus on selecting different alternatives during product realization. For instance, guiding the selection of materials, selection of design geometries with high durability, and optimization of manufacturing processes parameters for reducing energy intensity.

As shown in Table 1, some prior work can be classified into multiple categories. Most of the reviewed work can be classified as either C-1 (11/21) or C-2 (9/21), with very few of the work focusing on C-3 (3/21). Thus, simulation models for selection of design alternatives in DfCE are sparse compared to their usage for C-1 and C-2. This is primarily because it is challenging to connect design attributes to the lifecycle process and their impacts on product circularity without establishing proper methods and tools for the same.

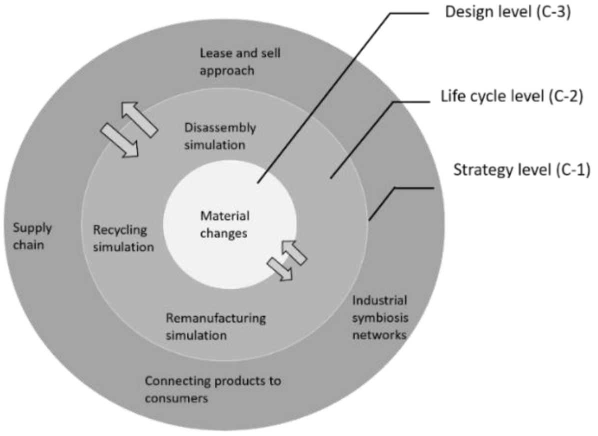

Figure 1. Classification of Circular Economy Simulation Models by Objectives

The relationships between the three categories (C-1, C-2, C-3) are also evident when viewed from the perspective of the simulation model scope in their application domain, viz., *design level* (modelling the circularity performance of processes involved in the creation of a physical artifact), *life cycle level* (modelling technical product circularity performance across one or more life cycle stages), and *strategy level* (modelling underlying techno-economic systems characterising product circularity). Figure 1 illustrates the nested nature of relationships between the above levels. C-1 corresponds the outer perimeter, i.e., *strategy level,* involving simulation models that represent major overhauls for a manufacturing company. Herein, the models are used to explore changes such as adoption of new business strategies, e.g., transitioning to a lease and sell approach, and macro-level improvement strategies such as developing connected (intelligent) products, supply chain optimisation, and closing resource loops by e.g., adopting industrial symbiosis. The intermediate layer (*life cycle level)* corresponds to C-2, wherein simulation models focus on improving circularity across one or more lifecycle stages. For instance, simulating the product use phase to extend product lifetimes, simulating optimal remanufacturing policies, simulating disassembly and recycling stages. The inner layer represents the *design level,* wherein simulation models are used to explore the effects of changes to product and process design parameters (e.g., material substitution, changes in manufacturing process) on the resulting CE performance of the product and/or process (C-3). The simulation models used in these three layers are not independent of each other as the CE concept is multi-scale (Saidani et al., 2019) and couplings between the layer can significantly influence CE. For instance, changing product material and geometry (*design level*) can influence its use-phase durability (*life cycle level*), which in-turn affects the economic success of implementing a PSS model (*strategy level*). Conversely, a top-down influence can be exerted in a similar manner; a viable end-of-life take-back strategy may require the creation of new disassembly practices and force a change in product architecture. Developing such multi-level simulation models is complex, and an open research challenge (ACCURATE, 2024) . A first step in enabling such simulations, is addressing the relative lack of simulation-based approaches for CE at the design level (C-3); this gap exists despite the relative richness of engineering models and simulation-based tools capable of modelling technical product and performance of products (e.g., finite-element based tools for structural design optimisation, manufacturing cost and quality optimisation). This is because the computation of the CE indicators primarily requires aggregate resource and energy flows. Therefore, it is difficult to establish a causal relationship between the product design-related parameters and the CE indicators at the product realization stage. Some work has been done towards addressing this gap. Aher et al., 2023a introduced a conceptual framework for circular product design through lifecycle process simulation models used at different product lifecycle phases, including their interdependencies within each phases. The conceptual model connects product design attributes with CE indicators through lifecycle process simulation models. However, their study did not consider dependencies between process parameters and product attributes. For instance, manufacturing process parameters (e.g., punching velocity) are affected by the selected design geometry, and together they influence CE indicators related to manufacturing energy consumption. Such dependencies between design and manufacturing can also constrain product-related CE indicators e.g., manufacturing feasibility can limit the quantity of recycled materials incorporated in a product. Therefore, modelling and simulation of design-manufacturing dependencies can, in several cases, aid decision-making in DfCE. The unit manufacturing process (UMP) models can effectively address this gap by considering the effect of parametric product design & process-related attributes on corresponding product lifecycle resource flows and, consequently, on the CE indicators for the manufacturing phase of the product lifecycle.

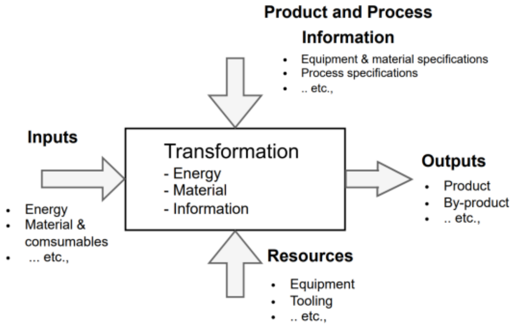

Figure 2. Graphical representation of unit manufacturing process information model used for sustainability assessment (ASTM, 2016)

A detailed UMP model can accurately model the effects of complex factors such as the effects of machine parameters like variation in cutting speed and tool path changes on the environmental impacts of a manufacturing process. Standards such as the ASTM E3012-20 (ASTM, 2016) have been developed to provide an approach to systematically categorize different manufacturing processes to capture the relevant environmental information. The standard formally defines the UMP information model as '*a model of a physical process in a manufacturing setting that adds value through the modifications or transformation of shape, structure, or a property of input material or workpiece.*' Figure 2 shows the graphical representation of the UMP model showing energy, material, product & process information, and the resources as input to the model and the finished product as the output along with the co-products. There have also been efforts to systematize the collection and representation of manufacturing process through the development of the unit process lifecycle inventory (UPLCI) methodology and applied to a wide range of manufacturing processes (Kellens et al., 2012, Raoufi et al., 2020, Glišić et al., 2021). More recently, Raman et al., 2022 introduced a methodology to extend the prior framework development efforts by ASTM standards to introduce the reusability and extensibility of the UMP models. They defined the template model as a standard UMP model and a layer model encapsulating it to extend the template model to user-specific information models. Thus, the UMP models, which abstract manufacturing processes to model material and energy exchanges in a unit process (e.g., injection molding, milling), are predominantly utilized in sustainability assessments, and the application of these models for both CE and sustainability assessments remains limited based on the conducted review.

To this end, the remainder of this article discusses using UMP modelling and simulation to support DfCE. This paper, thus, aims to showcase the use of UMP models for DfCE at level C-3 by combining circularity and sustainability (C&S) assessment of manufacturing processes. Specifically, we focus on highlighting:

1. Modelling dependencies between design-manufacturing parameters through using multiple sub-models (including using the UPLCI methodology) for estimating manufacturing resource use performance.

2. Simulation-based estimation of environmental sustainability indicators and CE indicators for unit manufacturing processes.
3. Analysing the sensitivity of the above indicators to changes in design and manufacturing process parameters.

3 Case Study

In this case study, we discuss the first step towards adapting UMP models for DfCE by demonstrating C&S assessment for an injection molding (IM) UMP that is used to manufacture a PVC flange coupling. The focus is on demonstrating that the UMP model can capture complex interdependencies between design parameters (e.g., material selection) and manufacturing process parameters, to subsequently generate a causal understanding of how they affect the C&S performance of the product as well as the manufacturing system.

To this end, the developed UMP model enables the PVC flange coupling to be manufactured using different percentages of recycled PVC material. The effects of changes in nominal values of manufacturing parameters (±60% of their nominal value) and material (100% virgin PVC; 50% recycled PVC) on two indicators: CE indicator energy intensity (EI) (Jerome et al., 2022) and the environmental sustainability indicator global warming potential (GWP) is analysed. The IM UMP model consists of three sub-models: (i), PVC IM CFD simulation model, (ii) UPLCI IM energy consumption simulation model, and (iii) auxiliary IM lubrication consumption model. These models require product design information and manufacturing process parameters as inputs (shown in Figure 3) and together, they estimate the inventory data for calculating GWP and EI of the overall model. The injection molding CFD model was implemented in COMSOL Multiphysics® simulation software. The other two sub-models were implemented in the MathWorks® MATLAB 2023a environment. The overall UMP model is simulated in MATLAB 2023a environment through COMSOL Multiphysics® application programming interface.

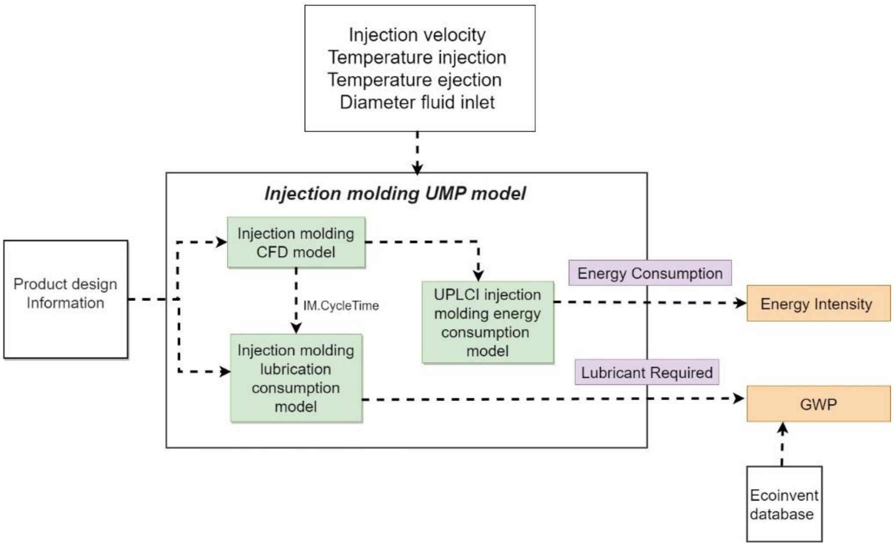

Figure 3. Injection Molding (IM) UMP model for PVC flange production

The three sub-models used are briefly explained below:

- **IM CFD simulation model:** This model simulates the CFD simulation of the molten PVC filling into the mold. The output from this model is the energy required for injecting the fluid into the mold and the total cycle time required for the injection molding operation. The viscosity of the polymer injected in this model changes with the amount of recycled content in the product. Thus, affecting the energy required for injection molding the polymer. The output from the IM CFD simulation model, i.e., energy consumed in the IM process and the cycle time is given to the UPLCI IM simulation model. Meanwhile, only the cycle time information is given to the IM lubrication consumption model.
- **UPLCI IM simulation model:** The UPLCI model (Raoufi et al., 2020) calculates the energy consumption of the injection molding and peripheral systems, such as basic, polymer melting, packing, and cooling energy.
- **IM lubrication consumption model:** The IM lubrication model uses the cycle time data from the IM CFD model to get the amount of coolant consumed for cooling purposes. It is calculated based on specific water consumption which is a function of coolant required per shot, mass of the part and number of cavities in injection molding. For this case study, it is assumed that there is no recirculation of the lubricant for cooling purposes.

Furthermore, EI is estimated using Equation 1 as shown below.

$EI = \frac{E_{extraction}+E_{manufacturing}-E_{int}}{m_{product}+m_{co-product}}$ *(1)*

In the above equation, $E_{extraction}$ presents energy used in the extraction phase, $E_{manufacturing}$ is the energy used in the manufacturing phase, E_{int} is internally derived energy, $m_{product}$ is mass of the product, and $m_{co-product}$is mass of the co-product. The sustainability indicator is the global warming potential (GWP), calculated through the energy usage and lubricant consumption obtained from the UMP model using an Ecoinvent 3.5 apos database and the IPCC 2013 Climate Change GWP100a impact assessment method.

As shown in Figure 3, the IM UMP models was analysed for variations in four manufacturing process parameters: (i) diameter of the fluid inlet to the mould (D_{inlet}), (ii) ejection temperature (T_e), (iii) melting temperature (T_m), (iv) injection velocity (U_{in}), and one relevant design parameter*:* (i) fraction of virgin material used in manufacturing the PVC flange (R_{frac}). These parameters were selected as they represent controllable parameters in IM processes and play a crucial role in obtaining the net shape of the final part (Kashyap and Datta, 2015, Lee et al., 2015).

As discussed earlier, to observe the changes in EI & GWP, the overall IM UMP model was executed (simulated) with each of the four manufacturing parameters adjusted to ±60% of its nominal value with 10 samples in the steps of 10% for scenarios involving 100% virgin PVC and 50% recycled PVC. Due to the computational expensiveness of running the IM UMP model, outputs from 77 discrete executions of the model are used to train regression models for estimating relationships between the five parameters ($D_{inlet}, T_e, T_m, U_{in} R_{frac}$) and EI, GWP. This enables a more continuous exploration of the design space and to potentially optimise the IM process. Apart from these input parameters, we also explore the influence of cycle time (T_{cycle}), an intermediate variable from the IM CFD simulation model, on EI & GWP. This exploration serves to demonstrate the potential for investigating and optimising UMP sub-models with respect to their contributions to the overall C&S performance of the UMP model.

4 Results & Discussion

Table 2 shows the built regression models for the outputs obtained from the simulation models for the EI and GWP as a function of $D_{inlet}, T_e, T_m, U_{in}, R_{frac}$ and Table 3 lists the corresponding significant parameters ($p < 0.005$) in the regression modelling. Standard least square regression models were used to fit the data. It can be observed from the regression coefficients that EI and GWP are negatively correlated with D_{inlet}. This is because the energy required for fluid injection decreases with an increase in D_{inlet}. The parameters T_m and T_e are respectively positively and negatively correlated to EI and GWP. This correlation for $T_m$and T_e can be attributed to changes in the value of the temperature difference (T_m-T_e); the higher the value of (T_m-T_e), the higher the value of EI and GWP, due to more energy required to cater to a large temperature difference. Both EI and GWP are negatively correlated to U_{in} as an increase in U_{in} results in a decrease in the T_{cycle}, lowering the overall energy and lubricant consumption. It can also be observed that the changes in EI and GWP are concordant (sign of regression coefficients in Table 2), when considering the changes in the above manufacturing process parameters. This is valuable information in the context of this study, as the efforts can be concentrated on simultaneously improving both indicators. A change in R_{frac} heavily affects EI as material extraction energy significantly decreased with increase in recycled content; additionally material extraction energy dominates manufacturing energy use in this study. However, GWP is unaffected as it only measures CO_2 eq. emissions related to the IM process, and a change in R_{frac} does not significantly influence process energy consumption or lubricant use.

Table 2. Regression coefficients for EI and GWP

Parameter	**Coefficient in the EI Equation**	**Coefficient in the GWP Equation**
D_{inlet}	-0.0055 * log(D_{inlet})	-0.0016 *log(D_{inlet})
T_e	-0.0071 * log(T_e)	-0.0022*log(T_e)
T_m	+0.0182 * log(T_m)	+0.0066*log(T_m)
U_{in}	-0.0063 * log(U_{in})	-0.0019*log(U_{in})
R_{frac}	+0.9750 * log(R_{frac})	+0.0001 *log(R_{frac})

Table 3. Significance of input parameters for estimating EI, GWP, T_{cycle} ($p < 0.005$)

Indicators	Significant parameters (p < 0.005)
EI	$D_{inlet}, T_e, T_m, U_{in}, R_{frac}$
GWP	$D_{inlet}, T_e, T_m, U_{in}$

We take one step further and observe the effect of one of the intermediate variables from the IM CFD simulation model (T_{cycle}), on GWP and EI. Figure 4 shows a 3D scatter plot between T_{cycle}, GWP, and EI, color-coded with the variation in the parameters (D_{inlet}, T_e, T_m, U_{in}, R_{frac}). It can be observed from Figure 4 that the value of EI is unaffected with changes in GWP and T_{cycle}. At the same time, T_{cycle} proportionally increased with GWP. This is because an increase in T_{cycle} results in higher energy and lubricant consumption, increasing the value of GWP, whereas the value EI is loosely dependent due to the higher contribution from the extraction phase to the energy consumption compared to the manufacturing phase.

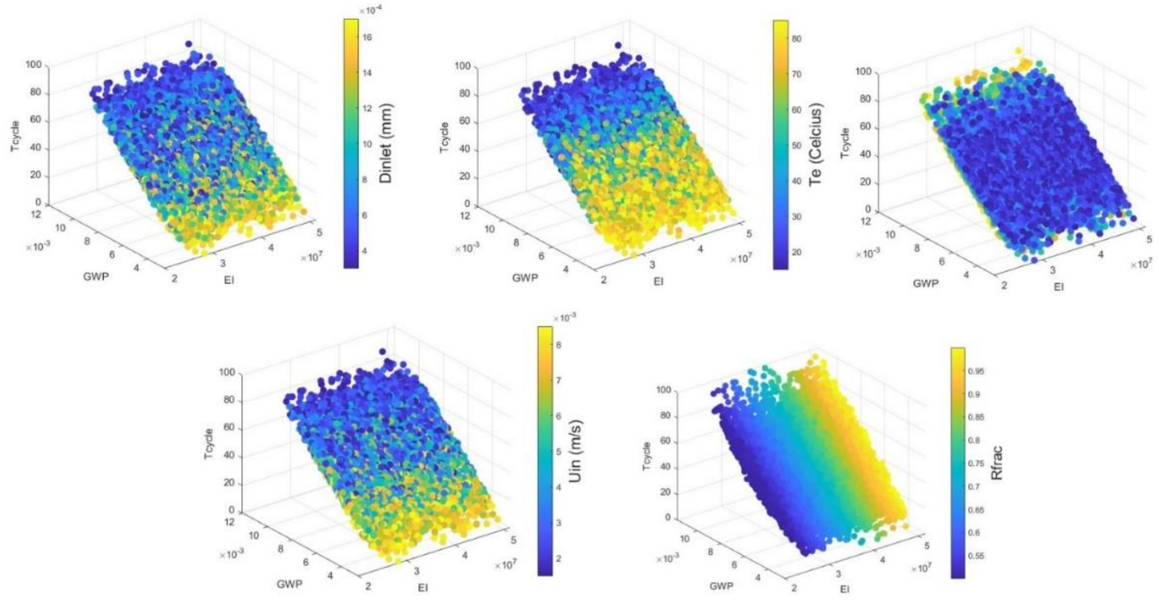

Figure 4. 3D Scatter Plot of T_{cycle}, GWP, and EI, Colored by Variations in D_{inlet}, T_e, T_m, U_{in}, R_{frac}

The case study on the IM UMP model demonstrates that insights concerning the implementing CE and sustainability strategies (e.g., change in process parameters and materials) at the design level (C-3) can be generated through manufacturing simulation. For instance, decreasing EI via introduction of more recycled content, decreasing EI and GWP simultaneously by decreasing T_m. The knowledge of the CE and sustainability behaviour can help narrow the efforts for CE strategy selection and implementation in manufacturing. For instance, in this case study there are little conflicts between the two indicators and changing process parameters to reduce GWP also benefits EI. However, in other cases, the presence of conflicts could enable the identification of Pareto-optimal design and process parameters that balance C&S performance. Furthermore, the ability to develop UMP models in a modular manner enables them to be readily adapted towards real-world implementation, wherein the architecture of machines and processes may differ. To illustrate, the IM lubrication consumption model and can be updated/swapped in for an IM machine that uses a different lubrication setup, while the other sub-models could remain the same. Finally, in this case study we demonstrated using the IM UPLCI model for estimating IM energy use. A wide variety of UPLCI models (e.g., milling, drilling, grinding, welding) have been developed and validated by the sustainable manufacturing community, and reusing such models for manufacturing CE assessment is advantageous as they are also able to assess manufacturing sustainability performance. The case study concentrated on a single product in a product system. However, in a product system consisting of multiple parts, the analysis can be focused on the critical parts of the product identified based on parameters such as mass, cost of implementation, the margin of improvement, etc.,

This case study focused on the C-3 (design) level usage of simulation models. Consequently, the CE and sustainability indicators analysed in this study (EI and process GWP) closely correspond to this level. However, the overarching goal of this work is to enable the coupling of such process simulation models with models at the lifecycle level (e.g., C-2: modelling use phase durability) and the strategy level (e.g., C-1: modelling profitability of PSS strategies) for more holistic CE assessment. Approaches for developing such multi-scale simulation models for CE are not commonplace. Despite the potential benefits, simulation modelling at each level could be cumbersome, and it may not be helpful. For instance, a simulation model focusing on a design-related parameter *(design level)* concerning a CE strategy may be unrelated to the broader business strategy *(strategy level)*. To further illustrate based on the case study results, causal links between a C-3 level parameter e.g., (T_{cycle}) and C-2 and C-1 level CE indicators e.g., material circularity indicator (MCI) and material intensity of profits, required combining the IM UMP model with use-phase simulation models for the PVC flange, and business/market simulation e.g., using systems dynamics models. To effectively implement such comprehensive models for DfCE, it's crucial to identify and map the dependencies among critical simulation parameters at each level, minimising computational effort, while still providing useful insights for selecting and improving CE strategies across these levels. Further research is needed on understanding the feasibility and utility of building such comprehensive models.

5 Conclusions

In this paper, we review the usage of simulation models for DfCE. We categorized the simulation models based on their usage for CE-related business strategies, CE-related lifecycle stages and the CE-related selection of design alternatives. We then showcased the need for usage of UMP simulation models for DfCE and the requirements for the same. This was illustrated through a manufacturing simulation of a PVC flange coupling through the usage of UPLCI models, considering both design and design-related process parameters. We also discuss the challenges for holistic usage of simulation models for DfCE. Future research should aim to clearly identify and analyze the relationships among simulation parameters related to the DfCE across the three levels.

Acknowledgements

This research conducted in this paper is supported by the Aarhus University Research Foundation and by the European Union’s Horizon Europe research and innovation program under grant agreement No. 101138269, project ACCURATE (Achieving Resilience Through Manufacturing As A Service, Digital Twins And Ecosystems). The findings and opinions stated in this paper reflect the opinion of the authors and not the opinion of the European Commission. The authors would like to thank Marija Glisic and Giovanni Formentini from the Department of Mechanical and Production Engineering, Aarhus University, for their detailed feedback.

References

ACCURATE, 2024. Achieving resilience through manufacturing as a service, digital twins, and ecosystems (ACCURATE).

Acerbi, F., Sassanelli, C., Terzi, S., Taisch, M., 2021. A Systematic Literature Review on Data and Information Required for Circular Manufacturing Strategies Adoption. Sustainability 13, 2047.

Aher, G., Boudjadar, J., Ramanujan, D., 2023a. Towards Simulation-Based Circular Product Design. Procedia CIRP 116, 690-695.

Aher, G., Macedo, H.D., Larsen, P.G., Ramanujan, D., 2023b. Supporting Design for Circular Economy Using Lifecycle Co-Simulation, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V005T005A006.

Ameli, M., Mansour, S., Ahmadi-Javid, A., 2019. A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility. Resources, Conservation and Recycling 140, 246-258.

ASTM, 2016. Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes ASTM E3012-16. ASTM International, West Conshohocken, PA.

Bal, A., Badurdeen, F., 2022. A simulation-based optimization approach for network design: The circular economy perspective. Sustainable Production and Consumption 30, 761-775.

Bernstein, W.Z., Tensa, M., Praniewicz, M., Kwon, S., Ramanujan, D., 2020. An automated workflow for integrating environmental sustainability assessment into parametric part design through standard reference models. Procedia CIRP 90, 102-108.

Bosch, T., Verploegen, K., Grösser, S.N., Van Rhijn, G., 2017. Sustainable Furniture that Grows with End-Users, Dynamics of Long-Life Assets. Springer International Publishing, pp. 303-326.

Charnley, F., Tiwari, D., Hutabarat, W., Moreno, M., Okorie, O., Tiwari, A., 2019. Simulation to enable a data-driven circular economy. Sustainability 11, 3379.

Fraccascia, L., Yazan, D.M., 2018. The role of online information-sharing platforms on the performance of industrial symbiosis networks. Resources, conservation and recycling 136, 473-485.

Franco, M.A., 2019. A system dynamics approach to product design and business model strategies for the circular economy. J Clean Prod 241, 118327.

Gaspari, L., Colucci, L., Butzer, S., Colledani, M., Steinhilper, R., 2017. Modularization in material flow simulation for managing production releases in remanufacturing. Journal of Remanufacturing 7, 139-157.

Glišić, M., Veluri, B., Ramanujan, D., 2021. A reusable unit process life cycle inventory model for infeed centerless grinding, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V005T005A025.

Hannula, J., Godinho, J.R.A., Llamas, A.A., Luukkanen, S., Reuter, M.A., 2020. Simulation-Based Exergy and LCA Analysis of Aluminum Recycling: Linking Predictive Physical Separation and Re-melting Process Models with Specific Alloy Production. Journal of Sustainable Metallurgy 6, 174-189.

Hao, Y.H., Wang, L.M., Qiu, L.X., 2012. System dynamics simulation and adjustment on coal resource utilization based on circular economy. Advanced Materials Research 524, 3190-3201.

Innocenzi, V., Ippolito, N.M., Pietrelli, L., Centofanti, M., Piga, L., Vegliò, F., 2018. Application of solvent extraction operation to recover rare earths from fluorescent lamps. J Clean Prod 172, 2840-2852.

Jerome, A., Helander, H., Ljunggren, M., Janssen, M., 2022. Mapping and testing circular economy product-level indicators: A critical review. Resources, Conservation and Recycling 178, 106080.

Kashyap, S., Datta, D., 2015. Process parameter optimization of plastic injection molding: a review. International Journal of Plastics Technology 19, 1-18.

Kellens, K., Dewulf, W., Overcash, M., Hauschild, M.Z., Duflou, J.R., 2012. Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO 2 PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. The international journal of life cycle assessment 17, 69-78.

Lee, J.-M., Moon, J.-S., Lee, H., Choi, B.-H., 2015. Investigation of fatigue and mechanical properties of the pipe grade poly (vinyl chloride) using recycled scraps. Express Polymer Letters 9.

Low, J.S.C., Ng, Y.T., 2018. Improving the economic performance of remanufacturing systems through flexible design strategies: a case study based on remanufacturing laptop computers for the Cambodian market. Business Strategy and the Environment 27, 503-527.

Matino, I., Colla, V., Baragiola, S., 2017. Electric energy consumption and environmental impact in unconventional EAF steelmaking scenarios. Energy Procedia 105, 3636-3641.

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resources, Conservation and Recycling 140, 305-312.

Nishino, N., Kimita, K., Ito, T., 2022. Mechanism for matching circular products and customers with top trading cycles. CIRP Annals 71, 5-8.

Odenbreit, C., Kozma, A., 2019. Dismountable flooring systems for multiple use, IOP Conference Series: Earth and Environmental Science. IOP Publishing, p. 012028.

Pfaff, M., Glöser-Chahoud, S., Chrubasik, L., Walz, R., 2018. Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures. Resources, Conservation and Recycling 139, 205-218.

Raman, A.S., Morris, K.C., Haapala, K.R., 2022. Reusing and Extending Standards-Based Unit Manufacturing Process Models for Characterizing Sustainability Performance. Journal of Computing and Information Science in Engineering 23.

Raoufi, K., Harper, D.S., Haapala, K.R., 2020. Reusable unit process life cycle inventory for manufacturing: metal injection molding. Production Engineering 14, 707-716.

Reuter, M.A., van Schaik, A., 2015. Product-centric simulation-based design for recycling: case of LED lamp recycling. Journal of Sustainable Metallurgy 1, 4-28.

Roci, M., Salehi, N., Amir, S., Shoaib-ul-Hasan, S., Asif, F.M., Mihelič, A., Rashid, A., 2022. Towards circular manufacturing systems implementation: a complex adaptive systems perspective using modelling and simulation as a quantitative analysis tool. Sustainable Production and Consumption 31, 97-112.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. J Clean Prod 207, 542-559.

Sassanelli, C., Rosa, P., Terzi, S., 2020. Circular Economy-oriented Simulation: A Literature Review Grounded on Empirical Cases. IN4PL, 53-59.

Teekasap, P., 2018. National economic benefits of circular economy policy, 2018 5th International Conference on Business and Industrial Research (ICBIR). IEEE, pp. 486-490.

Walzberg, J., Carpenter, A., Heath, G.A., 2021. Exploring PV circularity by modeling socio-technical dynamics of modules' end-of-life management, 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). IEEE.

Yazan, D.M., Fraccascia, L., 2020. Sustainable operations of industrial symbiosis: an enterprise input-output model integrated by agent-based simulation. International Journal of Production Research 58, 392-414.

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