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A total life cycle approach for developing predictive design methodologies to optimize product performance

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Abstract

Sustainable products must be designed by considering how design decisions impact their total life cycle (TLC) sustainability content. Even more so important when designing products to incorporate the technological elements of sustainable manufacturing, the 6Rs (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture), to achieve Circular Economy (CE). This paper presents the preliminary work of an ongoing research project on developing a novel framework incorporating predictive models with TLC considerations. This unique approach develops and integrates models with associated risks, and optimizes for maximizing the sustainability benefits due to design decisions. Such predictive capability is extremely useful for process planning, where careful planning and optimization of process conditions would allow inducing favorable product performance and improved sustainability.

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Keywords: Sustainable Manufacturing; Product Design; Design for Sustainability; DFS; Predictive Modeling; Performance Optimization;

1. Introduction

Applicable processes to manufacture a product depend on the features and/or functionality expected from the product being designed. Conversely, performance and/or functionality of the product depends on the manufacturing processes employed to produce the product. While recent progress in concurrent engineering helps to improve current product design practices, lack tools to support the concurrent engineering at the product design stage is a major

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problem, particularly when the impacts of design decisions on the product performance and sustainability needs to be considered.

The conventional product design process involves the salient steps expressed in Fig. 1. After identifying the customer needs, the product features and functions are established, oftentimes only with speculative knowledge of the process capabilities. After establishing (at least a major part of) the product design, relevant processes are selected and optimized. Process selection and optimization are usually done with the knowledge and experience of the designers, often only by considering the manufacturing concerns. This procedure often lacks adequate consideration of product performance, life and sustainability. If the product sustainability aspect was considered at the early stages of the product design, actual sustainability content of the manufactured product, including the product performance and life, can be significantly improved.

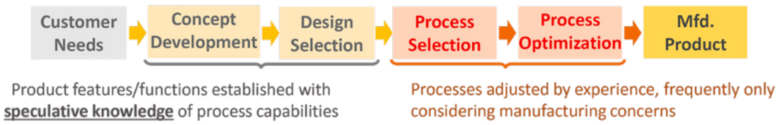

Fig. 1 Conventional product design process

This paper presents the preliminary work of an ongoing study investigating the process-induced performance and sustainability impacts and the opportunities to improve total life cycle (TLC) product sustainability by careful planning and optimization of the manufacturing processes, at the product design stage. The scope of this study is limited to the component level of products (i.e., simple stand-alone products). However, through appropriate modeling and optimization of critical components, profound improvements in terms of TLC product sustainability and performance can be made to the overall (complex) product.

2. Literature review

While there is no standard definition for sustainable manufacturing, a recent work [1] provides a comprehensive definition for sustainable manufacturing: *"Sustainable manufacturing deals with three integral elements: products, processes and systems. To achieve sustainable production, each of these three integral elements is expected to demonstrate: (a) reduced negative environmental impact; (b) offer improved energy and resource efficiency; (c) generate minimum quantity of wastes; (d) provide operational safety; and (e) offer improved personal health, while maintaining and/or improving the product and process quality with the overall life-cycle cost benefit" [1]*. This definition incorporates the three elements of manufacturing (products, processes and systems) with sustainability triple bottom line (TBL), and shows the importance of considering total (overall) life cycle (i.e., TLC [2]).

2.1. Total life cycle (TLC)

Total life cycle (TLC) of manufactured products consists of the four major life cycle stages: Pre-Manufacturing – which involves the extraction of material and product/process development; Manufacturing – where semi-processed materials are transformed into finished products utilizing different processes; Use – which consists of the time a product is utilized by the user(s); and Post-Use - when a product reaches its end-of-life (EOL) and a use value of the product is lost [2].

As illustrated in Fig. 2, the 6R concept (*Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture*) [2-4] identifies how different end-of-life (EOL) options are linked into different stages of the TLC of a product. The 6R concept also highlights the need for purposeful planning of EOL activities during product design, in order to establish a closed-loop material flow. This is especially important for Circular Economy (CE), in which the 6Rs are identified as major technological elements [3].

The '*Reduce*' element of 6R is especially compatible and complementary with the *Lean manufacturing* principles [5]. Lean manufacturing is useful in implementing *Reduce* at the manufacturing process and systems levels [5]. In addition to the obvious conformity with *Reduce* due to the strive toward waste elimination in lean manufacturing, its core ideas of continuous improvement and systematic problem-solving mindset are highly applicable to sustainable product design [5]. This work also suggests a design feedback loop through the TLC to identify opportunities to continuously improve the product design process using the knowledge gained during each product life cycle. Data-supported predictive models will be highly useful in such scenarios, due to their ability to continuously improve progressively with the new knowledge/data gained.

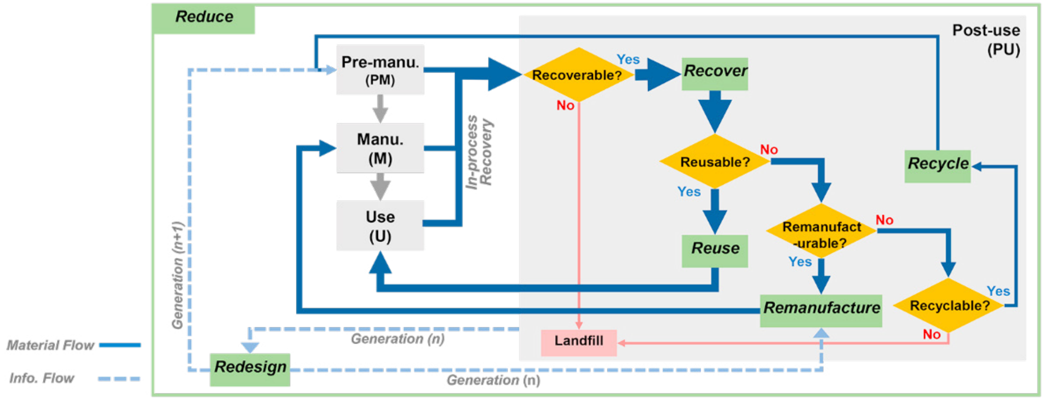

Fig. 2 Total life cycle of products and the 6R concept [4]

2.2. Design for Sustainability (DFS)

Major portion of a product's cost will be committed to by the end of product design stage. In order to have a significant impact on the environmental profile of a product, the environmentally-conscious features need to be introduced during its design stage [6, 7]. Thus, the product design stage is expected to make the highest influence on a product's TLC sustainability, at the least economic cost. Design for sustainability (DFS) (along with other '*DfX*' methods such as *Design for Environmental Impact*, *Design for Societal Impact*, *Design for Functionality*, etc., as discussed in previous literature and related principles such as '*Eco-design*' (terms which are often used interchangeable in literature) introduce sustainability principles during the product design stage [6-8].

A classification of these Eco-design tools identifies that a majority of quantitative tools available for detailed design stage are based on Life Cycle Assessment (LCA) [6]. However, LCA is confined only to the environmental aspect of sustainability. LCA data consists of uncertainties due to: imprecise or outdated measurements, utilizing simplification factors, neglecting the spatial or temporal characteristics, etc. [6]. Thus, LCA is only capable of providing information of generic products or processes [6]. At the detailed design stage, designers require explicit data on the sustainability content of specific products they are designing, along with indication of the sustainability impact due to the design decisions being made. Recently, more comprehensive product sustainability frameworks such as Product Sustainability Index (*ProdSI*) [9] have been established. While these sustainability evaluation methods are comprehensive, they are not design-oriented [10]. Key needs highlighted in DFS literature are: more analytical methods to integrate downstream life cycle impacts (with uncertainty quantification) [6, 10], and design support tools with optimization capability [11].

2.3. Sustainable processes and modeling

There is a wealth of research on modelling of sustainable manufacturing processes, to identify potential improvements including product performance [12, 13]. Product quality, life and performance are profoundly impacted by the processes used for manufacturing the components [12]. Favourable properties can be induced on components by choosing appropriate manufacturing process conditions. Surface integrity is identified as a key performance criterion for components, especially in applications such as aircraft and automobile industries [12, 14]. These process-induced improvements can eliminate the need for costly secondary processes or post-manufacturing treatments, such as special coatings or heat-treatments [14].

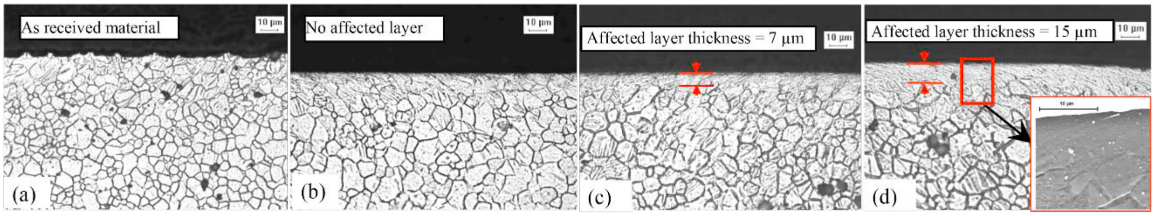

Fig. 3 Microstructure of *AZ31 Mg* alloy, (a) Before machining, and after, (b) Dry machining, cutting edge radius = 30 µm, (c) Cryogenic machining, cutting edge radius = 30 µm,, (d) Cryogenic machining, cutting edge radius = 70 µm [14]

Manufacturing process related advancements such as cryogenic machining, using liquid nitrogen as the metal working fluid (MWF), has the potential to induce favorable component properties while also being a more sustainable alternative [12-14]. For example, cryogenic machining of *AZ31 Mg* alloy illustrates how cooling method and edge radius of the cutting tool significantly impact the microstructure of the machined surface [14]. The impacts include an affected sub-surface layer with nano-grains (as depicted in the Fig. 3) of up to 15µm, which has an increased hardness of 95 HV (from the 55 HV on bulk material).

The need for models to predict the machining performance measures (surface roughness/surface integrity, cutting forces, etc.) and optimization methods are highlighted in the literature [12]. The improved predictive modeling capabilities are expected to enable planning for more desirable surface and subsurface characteristics in components, which leads to enhanced quality, life, performance, and ultimately sustainability of the assembled products [12].

2.4. Predictive modeling methods for DFS

In the previous literature discussing the use of mathematical modeling for engineering design, predictive modeling is promoted over descriptive ones, due to its ability to account for the uncertainties in real systems [15]. Predictive modeling for providing the decision support at the product design stage is relatively a new area of research. There has been a few recent published work [10, 16]. '*Normative Decision Analysis Method for the Sustainability-based Design of Products'* (NASDOP) [10] is one such model, which is based on the principle of normative decision-making for design optimization, and integrates the available LCA and Life Cycle Costing (LCC) data. NASDOP reduces the multi-attributes of the problem into a single attribute probabilistic function reflecting the decision maker's preference under uncertainty [10]. More recent literature extends predictive modeling for the application of material selection in sustainable design of products (MASSDOP) [17].

3. Development of a new framework

Primary concerns of design and manufacturing engineers when selecting manufacturing processes for a product are: production quantity; design complexity; and functional/material requirements of the product [18]. Product sustainability needs to be transformed from the current state of being a consequence of these primary concerns to a deciding factor [18]. Product sustainability impact due to the manufacturing processes utilized is distinctly dependent on the design features, functionality, and performance of a product [18]. Yet, most of the product sustainability evaluation methods do not consider product functionality or performance as major concerns.

As mentioned previously, planning for EOL activities is also a significant component in implementing sustainability at the product design stage. Thus, incorporating the 6R elements in the newly developed predictive model-based product design framework is an important task. As the design stage progresses, the need for more application-specific (explicit) design decision support increases [11]. Towards the detailed design stage, where the final product design and the relevant manufacturing process selections are done, predictive model-based tools are identified to be most effective [11]. A framework is being developed, based on the TLC product design process proposed in the previous work [11] (also illustrated in the Fig. 4, where: PM-Pre-Manufacturing, M-Manufacturing, U-Use, PU-Post-Use stages).

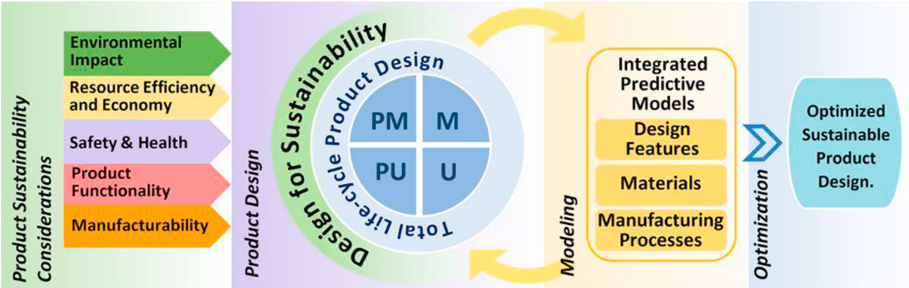

Fig. 4 Total life cycle product design stages (adapted from [11])

3.1. Performance Influencing Parameters (PIP) available at product design stage

Through an investigation of the parameters available for the designers to influence the component/product performance, following performance influencing parameter (PIP) types were identified at the component level:

i. *Design feature (or configuration) related parameters:* The primary PIP designers modify the design to achieve the customer (and performance) requirements. These include size, shape, tolerances of dimensions, types of joints use, etc.
ii. *Material property related parameters:* Generally, the material for design is selected due to its properties, which determine the product's performance. Most-commonly considered types of material properties include: acoustic, chemical, electrical, mechanical, thermal, etc.
iii. *Manufacturing process-induced parameters:* Typically, a combination of the previous two PIP, occurred due to the manufacturing processes utilized. During manufacturing, the processes can induce changes to the design features (e.g., surface roughness, thickness, etc.) and/or material properties (hardness, residual stresses, etc.). The changes can be unfavorable or even catastrophic when they are unintentional. However, through careful selection and optimization of manufacturing process conditions, there exists a possibility for inducing favorable parameters, further improving both the product performance and the sustainability content.

While all three types of these parameters are responsible for the component (and the resulting product) performance and sustainability, the third type is often neglected at the design stage due to complexities involved in determining the impacts and the lack of decision support tools. Current parametric design software packages are capable of guiding the designers to identify and optimize the design features and the material selection of a product. Yet, current software still lacks the ability to provide the same guidance to identify the optimal manufacturing process conditions which will induce vital product performance and sustainability improvements. In order to take advantage of the third PIP type during product design, predictive models must be developed along with necessary optimization processes.

3.2. Predictive modeling supported DFS

In the newly developed model shown in Fig. 5, the sustainability concerns are incorporated with the customer needs, in order to establish sustainability as a primary consideration (rather than being a consequence of other decisions). These sustainability concerns include: Environmental impact; Resource efficiency and economy; Safety and health; Product functionality; and Manufacturability [11]. After the conceptual designs are developed and multiple candidates selected, predictive modelling is utilized to support decision making at the design selection and detailed design stages. Predictive models are developed for all three types of PIP identified. For the *Feature selection* and *Material selection*

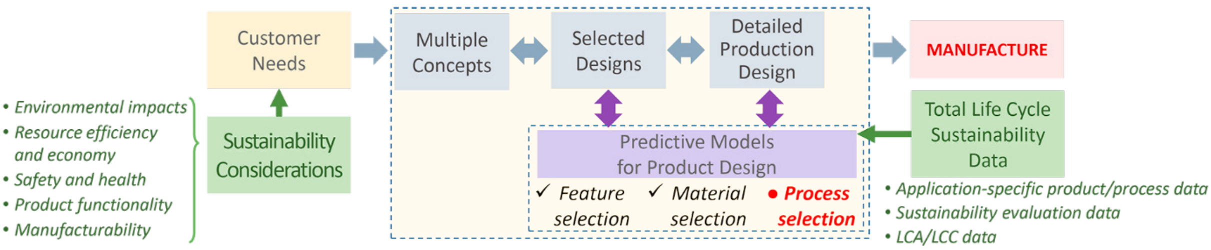

Fig. 5 Proposed enhanced product design process, supported by predictive models

PIP, the models available in literature are adopted. For the *Process selection*, the approach proposed in this study is to be utilized. The predictive models will include TLC sustainability data from application specific product and process data, sustainability evaluation data, and LCA/LCC data.

3.3. Development of a general framework for predictive modeling supported DFS

A general framework to enable optimization of product performance and sustainability is illustrated in Fig. 6. The framework introduces a novel perspective to evaluate product performance and sustainability impacts due to design decisions, with respective to the TLC. Each of the four model classes: Resource sourcing effectiveness; Resource utilization efficiency; Product functionality; and EOL recoverability; has a primary focus on a stage of TLC. Further details provided in next section, focusing on the *Process* PIP branch.

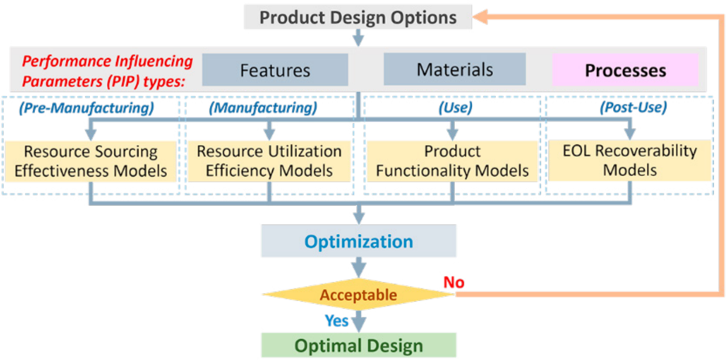

Fig. 6 Proposed general framework for predictive modeling supported DFS

3.4. A sub-framework for optimizing process-induced product performance and sustainability

The general model proposed is expanded for the *Process* PIP aspect. As illustrated in Fig. 7, first the relevant manufacturing processes and their major controlling parameters are determined. Sub-models for the four model classes discussed are developed based on metrics of *ProdSI* method, to identify how process parameters can be regulated to obtain optimal product performance and sustainability. Some of the applicable metrics proposed for *Process* PIP models are as follows:

- *Resource sourcing effectiveness class of models:* Percentage of renewable energy used for the selected process(es), Percentage of recycled material used in the selected process(es), Environmental impacts of sourcing consumables (ex: MWF, water, …), Injury rate (of processes), Health hazardous levels (of processes), etc.

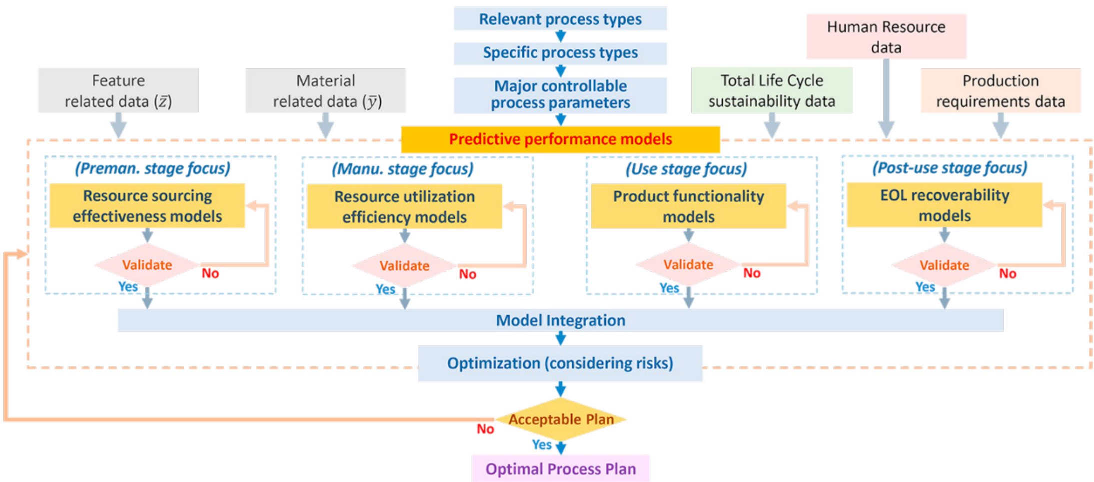

Fig. 7 Proposed framework for Process PIP optimization

- *Resource utilization efficiency class of models:* Energy efficiency (of processes), Total volume of material processed, Percentage of wasted material, Percentage of in-process recovery, etc.
- *Product functionality class of models:* Profitability, Return rate, Failure rate, Product's functionality specific indicators (e.g.: Wear-rate, Fatigue life, Corrosion resistance, …), Product customizability, Greenhouse gas emission during usage, Product ownership cost, Cost of maintenance, Safety ratings, etc.
- *EoL recoverability class of models:* Average disassembly cost, Average recovery cost, Expected percentage of EOL recovery, Reusability, Remanufacturability, Recyclability, etc.

When comparing different product or process options, the modeling procedure can be greatly simplified by taking a relative comparison by selecting a baseline design.

In order to integrate, following four sustainability impact (SI) factors are calculated for each of the model class:

SI_{RSE} = Sustainability impact due to Resource Sourcing Effectiveness models
SI_{RUE} = Sustainability impact due to Resource Utilization Efficiency models
SI_{PF} = Sustainability impact due to Product Functionality models
SI_{EOLR} = Sustainability impact due to End-of-Life Recoverability models

Process parameters: $\bar{x} = (x_1, x_2, \ldots, x_i, \ldots)$, e.g.: cutting speed, feed rate, depth of cut, MWF, etc.
Material property parameters: $\bar{y} = (y_1, y_2, \ldots, y_i, \ldots)$, e.g.: Young's modulus, thermal conductivity, etc.
Design feature parameters: $\bar{z} = (z_1, z_2, \ldots, z_i, \ldots)$, e.g.: surface roughness, area of functional surface, etc.

For the '*Process*' PIP type, the independent design variables will be process parameters ($\bar{x}$). Using the relevant material property parameters ($\bar{y}$) and design feature parameters ($\bar{z}$), both of which for the study of '*Process*' aspect of PIP, are set as constants.

Following additional capital cost factors are included at the integration of the sub-models:

i. *Technology acquisition cost factor (TA):* Guides deciding whether acquiring of new technologies to manufacture a product design is economically prudent. This amalgamates capital costs, such as the machine acquisition cost, facility upgrade cost, labor training cost, etc.
ii. *Changeover between processes cost factor (CP_{a-b}):* Amalgamates capital costs associated in changing from *process-a* to *process-b*, such as: process setup cost, specialist labor cost, transport cost, etc.
iii. *Product customization cost factor (PC):* Amalgamates capital costs associated with change of design when manufacturing customizable products, such as tooling change cost, design change cost, etc.

Inclusion of these three factors allows the designers to investigate the impact on the overall sustainability, with respect to the changing quantity of items produced or the customization levels, to determine the optimal process-options in each scenario.

Thus, the sustainable impact (per unit):

$$SI = S_{RSE} + S_{RUE} + S_{PF} + S_{EoLR} + \frac{1}{N}TA + \frac{1}{N}CP_{a-b} + \frac{1}{\tilde{N}}PC$$

For a complex product design with n-number of components, *m*-number of materials, and p-number of processes:

$$SI_{prod} = \sum_{1}^{n}\sum_{1}^{m}\sum_{1}^{p} SI_{RSE}(\bar{x},\bar{y},\bar{z}) + SI_{RUE}(\bar{x},\bar{y},\bar{z}) + SI_{PF}(\bar{x},\bar{y},\bar{z}) + SI_{EoLR}(\bar{x},\bar{y},\bar{z}) + \frac{1}{N}TA + \frac{1}{N}CP_{ab} + \frac{1}{\tilde{N}}PC$$

Simplifying for a single component, with a set material, and a set design (i.e., no customizations), the optimization problem becomes:

$$Min.\ \ S_{comp} = \left\{\sum_{1}^{p} S_{RSE}(\bar{x}) + S_{RUE}(\bar{x}) + S_{PF}(\bar{x}) + S_{EoLR}(\bar{x}) + \frac{1}{N}TA + \frac{1}{N}CP_{ab} + \frac{1}{\tilde{N}}PC\right\}$$

with respect to the design variables: $\bar{x} = (x_1, x_2, \ldots, x_i, \ldots)$,

Subject to the constraints: $y_k(\bar{x}) \leq C_k\ \ \forall k$, where the constraints related to the processes and component/product will be determined by the respective physical and material property limitations (e.g., maximum cutting speed, maximum temperature, etc.), component/product specifications (e.g., allowable surface roughness, required surface hardness, etc.), and the cost restrictions.

This work is continued towards developing the exact predictive models for each model class and to validate the framework. The risks will be factored in the optimization model, and a decision-making model, that takes designer preferences and their utility functions in to account, is being developed. The developed procedure is to be expanded in to a flexible design decision support tool, with application-specific customization capabilities.

4. Conclusions

Preliminary findings from an ongoing study to establish a TLC approach for developing predictive design methodologies useful for modeling and optimizing the product performance and sustainability is presented in this paper. This paper focuses on currently neglected opportunities, and provides a meaningful approach through careful optimization of manufacturing process conditions to induce favorable product performance and the sustainability content. Predictive model-based methods are identified to be most suitable for developing tools to realize these opportunities. Incorporating predictive models to enable informed decision making at the product design stage (including planning for end-of-life activities) is a critical step towards implementing Circular Economy. A framework with a novel perspective to evaluate the TLC impacts due to the design decisions, in terms of both product performance and sustainability is proposed. Inclusion of capital cost factors in the model integration allows designers to investigate possible manufacturing alternatives, while considering all three aspects of sustainability TBL. Necessary next steps are identified to develop these frameworks into tools supporting the product design process.

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