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A Framework for Material Selection in Multi-Generational Components: Sustainable Value Creation for a Circular Economy

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Abstract

Early stages of a product's design are critical for decisions impacting the entire life-cycle cost. Product designers have mastered the first generation, but they have no ability to know the impact of their decisions on multi-generational products. There is a need for tools that aim at closing the gap between total life-cycle information and the traditional design process. This paper presents a framework for a decision support tool that uses a combination of a life-cycle costing methodology and an evolutionary algorithm to assess design decisions specifically related to material selection. A case study is included to validate the new methodology.

Keywords: Circular Economy; Material Selection; Life-Cycle Costing; Product Design; 6R

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1. Introduction

Due to the reoccurring failure of the linear economy model's ability to meet the world's dynamic sustainability challenges, a new economic model is surging to the forefront. This concept, known as the circular economy (CE), is gaining acknowledgement among governments, corporations, and universities. The lead champion, the Ellen MacArthur Foundation [1], among others have recognized that today's world concurrently requires sustained economic growth, environmental protection, and societal wellbeing. However, often times, the circular economy concept being pushed in political arenas lacks a defined technical or engineering implementation. This is where the recently established 6R methodology for sustainable manufacturing (*Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture*) and new developments would be needed to create and define a new business model, bringing about sustainable value creation to different aspects of product design and manufacturing [2].

It is recognized that sustainable manufacturing is comprised of three core components: sustainable products, processes, and systems [3, 4]. The understanding of the integration of these

Nomenclature

$TLCC$	Total Life-Cycle Cost
C_{MFG}	Life Cycle Cost to Manufacturer
C_{CUST}	Life Cycle Cost to Customer
PM_i	Processing and Manufacturing Cost
RM	Raw Material Cost
RE_i	Recovery Cost
RRR_i	Recycle, Remanufacture, Reuse Cost
ES_i	Environmental and Societal Cost
Z_i	Case-Specific Costs
N_{1-N}	Sub-categories in Major Cost Categories
i	Indexing for sub-categories
G	# of Generations
x_3	% of new raw material needed
x_4	% of material recoverable
AC	Acquisition Cost
M_i	Maintenance Cost
U_i	Usage Cost
K	Profit Margin Factor
I	Incentivization Factor

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core elements into product manufacturing is critical in the development of quantitative predictive models [4]. It is also understood that sustainable manufacturing at product, process, and system levels must reduce environmental impact, improve efficiency, reduce waste, provide operational safety, and offer improved personnel health, while maintaining product and process quality with a total life-cycle cost benefit [2, 3]. This definition in itself creates a multi-dimensional problem that must logically be solved through some method of optimization. In order to solve this, life-cycle data must be integrated into the product design and manufacturing stages. An ability to design a product from the beginning with multiple life cycles in mind creates a significant advantage economically and can drive advancement in product and process technology.

This integration of life-cycle data into product design must be done at the most effective point of the design cycle. This effective point has been agreed upon by scholars to be prior to the conceptual design stage or as early as possible. Moreno et al. [5] and Saravi et al. [6] estimate that 70 to 80 percent of the life-cycle costs of a product are determined by product designers' decisions made in stages prior to the conceptual design stage. Figure 1 represents the cost commitment of design changes and the ability to influence the Triple-Bottom Line Impact (3BL: Economy, Environment, and Society) throughout the progression of the design cycle.

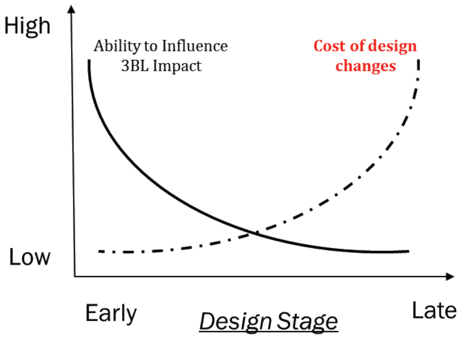

Fig. 1. Design cycle cost commitment

A product designer's material selection decision can critically influence the total life-cycle of a product material. This decision gives substance to a design and bridges the gap from concept to reality [7]. If not chosen correctly, selection of a material can trap a manufacturer into astronomical unforeseen costs. With the numerous materials at society's fingertips today, the possibility for this to occur is greater than ever. Thus, adequate consideration of the total life-cycle of these materials must be given in order to use these materials in the most efficient and profitable way.

This paper presents a novel framework for a decision support tool that assesses material selection in multi-generational components. This framework uses a combination of a life-cycle cost model based on the 6R methodology, traditional environmental and social metrics and indicators, and an evolutionary algorithm to assess design decisions specifically related to material selection.

As mentioned in the proposition, the framework is intended for multi-generational design. This adopts the cradle-to-cradle approach of sustainable manufacturing. From Toxopeus et al. [8], this approach aims at being a driving innovator in reaching sustainability goals. This concept is ingrained in the idea that any material should be viewed as food to the next generation of a product's life-cycle. This closed-loop approach not only targets the growing problem with depleting resources, but reimagines what was once considered waste into an economic asset for the future.

To satisfy the need of a component level assessment, the framework is also built at the component level. The term component can be subjective and can mean various things. For the purposes of this framework, a component is defined as a part of product that is required for functionality, performs a unique and necessary function in the operation of the product, is removed in one piece, and is indivisible for the use in the overall product.

2. Previous Work

2.1 Life Cycle Costing

Asiedu and Gu [9] recognized that there exists three types of cost models: conceptual, analytical, and heuristic. Each has its advantages and disadvantages. Conceptual models lack the ability to be applied to an in-depth analysis, but easily accommodate numerous systems. Analytical models are a series of mathematical relationships that can be generalized but often have to rely on many assumptions. Heuristic models are often specific to an application, but do not guarantee an optimal solution.

Asiedu and Gu [9] also claim that the cost models that are needed are ones that take into account the total life-cycle of a product, are implementable in the early design stages, and provide information to designers in a practical and usable format. In other words, there exists a need for a total life-cycle cost model that is accessible in the conceptual design stage and is user friendly in its implementation. Saravi et al. [6] suggest that there is a need for an early design stage cost model that would allow product designers to make more informed decisions.

2.2 Multi-Objective Optimization

As stated previously, for a decision that involves multiple variables and that has multiple considerations, the type of optimization that must be implemented is multi-objective optimization (MO). However, MO can be implemented in numerous ways. Various algorithms, mathematical models, and heuristics can be used in order solve a MO problem. Deb [10] summarizes a few of the most common methods: weighted sum and e-constraint method. In addition to these "classical" methods, there also exists methods known as evolutionary multi-objective optimization (EMO) such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO).

Often when designing a product, the material must satisfy multiple objectives: performance, lightweight, recyclability, cost, etc. There has been considerable research done in this