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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

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.

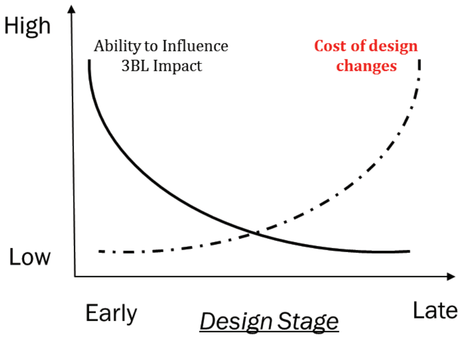

Fig. 1. Design cycle cost commitment

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 field, mostly involving the use of EMO. For example, Sakundarini et al. [11] use a GA for formulating a methodology for material selection of high recyclability. A case study was performed to show the proposed method was able to generate an optimal solution. Coello and Becerra [12] reviewed MO and its application in the field of material science, stating that MO has been used in order to determine things like material alloy percentages and processing characteristics. Coello and Becerra [12] also note that GA is the most widely used algorithm in the field, but recognize PSO as a potential alternative.

3. Methodology and Framework

Figure 2 is a flowchart that shows an overview of the proposed framework. The framework is composed of two distinct parts that are combined together to form a comprehensive method for sustainable material selection. These parts include a life-cycle cost model and an optimization algorithm. In addition to these two distinct parts, other data is proposed to be gathered from a traditional Life Cycle Assessment (LCA) database and social metrics that will need to be developed. Along with this, material properties specific to candidate materials and geometric properties specific to the design are passed as input to the algorithm.

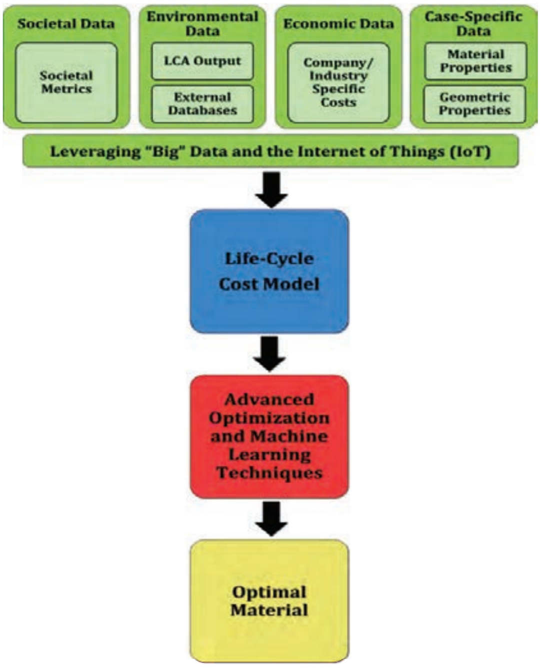

Fig. 2. Overview of the proposed framework

Procedurally, the framework progresses in three stages. The *first* stage involves collecting adequate data from external and/or internal sources in regards to material properties, costs, LCA results, and social performance indicators. Particular attention should be paid to the ability to collect data from existing devices that are already in the field. This is where leveraging the Internet of Things (IoT) can be useful in this particular application. The *second* stage involves using a developed 6R based life-cycle cost model [13] in order to determine the total life-cycle cost to the manufacturer and to the customer. The *third* stage involves using the calculated data collected in Stage one, along with the specific material properties and geometric properties of the component's design, as input into an advanced algorithm (in this case, a genetic algorithm was used).

3.1 Multi-Generational Methodology

Designers tend to only take into account a single generation of a product when making design decisions such as material selection. However, to be able to extend the view from single generation to multiple generations, the first generation must be completely understood. Shown in Figure 3 is a visual of the ideal material flow over a single generation. The material is first extracted from the earth, then it is processed into a workable material to be manufactured into a product. Following the use stage of the product, the product is *Recovered* and the material is placed into one of three streams: *Reuse, Remanufacturing, and Recycling*. What this does not show is the subsequent generations of the product during the *Redesign* phase. In addition, since this is the ideal material flow, Figure 3 does not show the waste stream following the use of the product. Instead, the idea is to adopt the circular economy concept of perpetual material flow and consider the recovered material as the food to the next generation of products.

Fig. 3. Ideal material flow over a single generation

Shown in Figure 4, the single generation view of material flow is extended to a multiple generational view. This

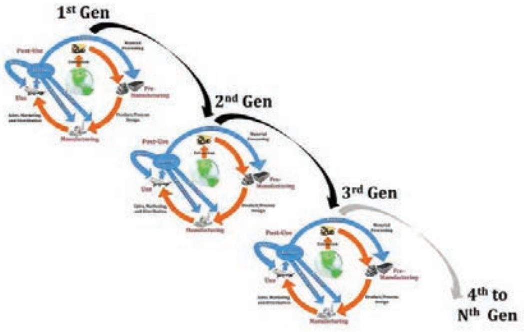

Fig. 4. Multi-Generational view of material flow [2, 13]

illustrates the *Redesign* stage. The helical pattern of moving from one generation to the next is supposed to represent utilizing the material from one generation to the next generation of products. This multiple generation consideration is what the proposed life-cycle cost model aims at implementing.

3.2 Life-Cycle Cost Model

As seen in Figure 5, the life-cycle cost model of the material flow is composed of two distinct areas: the manufacturer and the customer. This is an important distinction because they are two separate entities which make independent decisions; however, as seen in Rivera et al. [14], their decisions significantly affect one another. Breaking the cost into these two areas provides two significant advantages. First, simply calculating the total cost is ignoring which party is actually incurring that cost. The proposed approach aims at building in the structure of the reality of a manufacturer/customer relationship. The second advantage is that the designer can see the impact of the incurred costs to the manufacturer more directly than other approaches. In addition to these advantages, the multi-generational aspect gives an unprecedented ability to evaluate the total life-cycle.

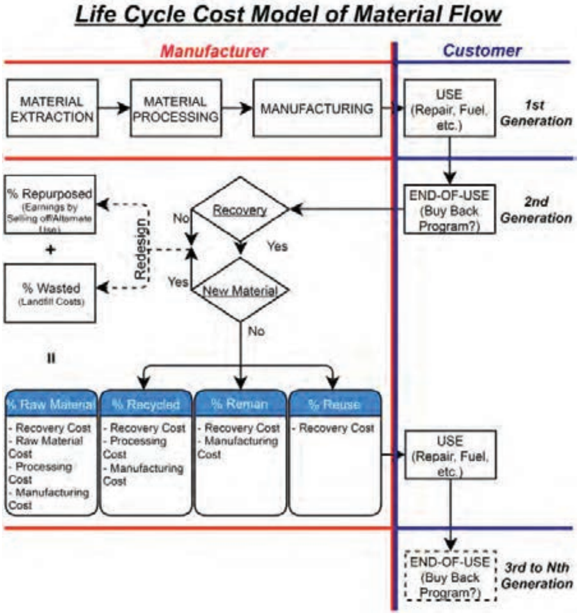

Fig. 5. Proposed total life-cycle cost model [13]

To understand the comprehensive nature of the cost model, the presence of the differing stakeholders must first be recognized. The customer and manufacturer represent the explicit stakeholders, while the environment and society represent implicit stakeholders. The goal of this model is aimed at sustainable value creation for all stakeholders, so all aspects of the life-cycle cost must be considered. Mathematically formulating the life-cycle cost model, the total life-cycle cost can be described by Eqn. (1).

$$TLCC = C_{MFG} + C_{CUST} \tag{1}$$

The term "total life-cycle cost" may seem ambiguous and unimportant from the singular perspective of the manufacturer or customer, but it goes back to the idea of sustainable value creation for all stakeholders involved. Although these two different costs are very different in nature, they both make-up the total cost footprint of the product. With that in mind, each of these two costs can be described in much more detail as in Eqns. (2) and (3). The cost to the manufacturer is defined as:

$$C_{MFG} = G\left[\left(\frac{1}{G} + (1 - x_4)\right)\left(RM + \sum_{i=1}^{N_1} PM_i\right) + x_4 \sum_{i=1}^{N_2} RE_i + (x_4 - x_3) \sum_{i=1}^{N_3} RRR_i \right. \tag{2}$$
$$\left. + \sum_{i=1}^{N_4} ES_i + \sum_{i=1}^{N_N} Z_i \right]$$

This equation can be broken down even further to each individual cost component's equation. For conciseness, those equations will not be included in this paper. One may notice that there are several constants that have been introduced in order to represent decisions made throughout the life-cycle. Specifically, x_3 represents the percentage of raw material that must be used in each subsequent generation. This is a result of the inefficiency in recycling, remanufacturing, and reuse as well as the percentage that is not recoverable. The more efficient the post-use process is, the less this factor plays into the calculation of the cost to the manufacturer.

There is alsox_4, which is the percent of material that is recoverable. This can be either by choice or due to the inherent efficiency in the process. The greater this percentage, the heavier the weight that is placed on RE_i and RRR_i. The customer cost equation is similar to the manufacturer cost equation and is defined as:

$$C_{CUST} = G\left(\left(\frac{1}{G} + I\right)(C_{MFG} * K) + \sum_{i=1}^{N_1} U_i + \sum_{i=1}^{N_2} M_i + \sum_{i=1}^{N_N} Z_i\right) \tag{3}$$

This equation can also be broken down further to each individual component's equation. The major difference that occurs in this equation is the presence of *I*. This factor is different than the multipliers used in the manufacturer equation; *I* is only applied to the acquisition cost. This factor represents the presence of an incentivized cost or reimbursement for returning the previous generation component. A good example of this is shown through the cell phone industry. Many companies are now offering a buy-back program where customers are reimbursed for trading in their old electronics for the newest version. This reimbursement lowers the acquisition cost of the next generation product [14].

Looking at the model graphically, Fig. 6 shows the life-cycle cost (*LCC*) benefit that can be reaped with each of the post-recovery material streams. Notice that this graph is not a constant relationship for all materials or all components, but is a snapshot for a given application. In other words, as the component or materials vary, this benefit curve will change as well [2, 13].

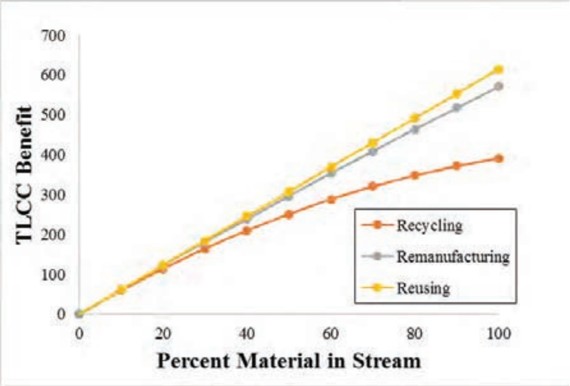

Fig. 6. LCC Benefit of the various post-recovery material streams [13]

From this graph, it can be seen that *Reusing* holds the highest economic benefit. This is consistent with what logic would say is true for most materials in common applications. One can also pull that *Remanufacturing* holds the second highest benefit which is also what logic would say is true for most materials in common applications. Lastly, if a material cannot be placed into such a high-value stream, then it is placed in the low-value stream of *Recycling.* For this particular material, a benefit is still seen, but it is considerably lower than the high-value post-recovery streams [2].

3.3 Optimization

The optimization algorithm chosen for implementation into the framework was a Genetic Algorithm (GA). This evolutionary algorithm was chosen because of its ability to handle multi-objective problems, its robustness, and its ease of implementation, along with its capability to escape local optima and reach a global optimum. Although a GA was used in the development of the framework, the framework is intended to be flexible to the adaptation to various machine learning and optimization techniques as long as the problem remains the same.

For this framework, there exists two types of objective functions. The first type is reserved for the maximization/minimization of the performance or functionality of the component. This can be anything as simple as the weight, or as complex as the buckling criteria and/or fatigue life of the component. The specific criteria and the number of criteria used is entirely dependent upon the designer's discretion and the component under evaluation. The second type of objective function is very similar to Type 1. The only difference is that it is reserved specifically for the life-cycle cost.

In addition to objective functions, there exists three different types of constraints that are used in the implementation of the GA. These include derived triple bottom line relationships, user-defined relationships, and user-defined geometric constraints. For conciseness, only the 3BL relationships will be discussed in this paper.

For the 3BL relationships, there are 4 different enforced relationships that are intended to be used to ensure there is improvement in the 3BL. The first relationship is the customer/manufacturer relationship. The intent of this relationship is to make the linkage between the cost to the manufacturer and the customer. The next relationship looks at ensuring the environmental impact improvement of the component. The third relationship takes the same form as the second, but with the only difference being the environmental impact is substituted for societal impact. The last 3BL relationship involves ensuring that the functional performance meets the failure criteria set forth by the designer.

4. Case Study

4.1 Data Collection and Formulation

The following case study is an academic illustration intended to show the relevance of the proposed framework. In addition, the case study allows specific areas of interest to be highlighted for further improvement. Also, for this illustration, it will be assumed that the first step of the framework has already been completed. In other words, the design objectives have already been identified, a loose geometry has already been chosen, and failure modes and critical design criteria have already been determined.

Since the first step is assumed to be completed, candidate materials must be identified to utilize the life-cycle cost model and to implement the optimization framework. The three generic materials will be described by the names Material A, B, and C. Table 1 shows the three generic materials and their respective considered material properties.

Table 1. List of Generic Candidate Materials

Material Property	**A**	**B**	**C**
Young's Modulus (GPa)	150	69	120
Density (g/cm^3)	1.5	2.2	3.5
Yield Strength (MPa)	110	95	730
UTS (MPa)	600	110	900
Shear Strength (MPa)	260	207	550
Brinell Hardness	88	95	334
Environmental Index (per cm^3)	0.58	0.65	0.68
Societal Index (per cm^3)	0.71	0.68	0.62

With these three materials, the life-cycle cost model must be implemented in order for it to be fed into the optimization framework. For the purposes of this illustration, the cost data will be broken down as shown in Table 2. This table shows the major cost elements that feed into the overall life-cycle cost. Following this, the geometric constraints and user defined constraints have to be defined in order to formulate the optimization process.

Table 2: Life Cycle Cost Elements for Candidate Materials

Cost Element	**A**	**B**	**C**
Manufacturer			
Raw Material Cost ($/kg)	22	3	2.1
Processing and Manufacturing Cost ($/kg)	18	3	2
Recovery Cost ($/kg)	0.5	0.5	0.5
Remanufacturing, Recycling, Reusing Cost ($/kg)	0.4	1	1
Remanufacturing	4.4	1	0.9
Recycling	18	3	2
Capital Recovery	-22	-3	-2.1
Environmental /Societal Relations Cost ($/kg)	28	14	9
Customer			
Acquisition Cost ($/kg)	Calc	Calc	Calc
Usage Cost ($/kg)	37	37	37
Maintenance Cost ($/kg)	42	34	31
Incentivization Factor	1	0.6	0.7

4.1 Results and Discussion

The optimization formulation was coded in MATLAB to utilize its multi-objective Genetic Algorithm (GA) toolbox. The GA toolbox was then used to run the three cases of two, five, and ten generations to capture a result for each case. The algorithm was run for 200 generations, and then the population was examined to determine convergence. A summary of the results can be seen in Table 3 where *R, t, L, BF* represent arbitrary geometric dimensions used to illustrate the application.

Table 3: Summary of Results for each Case Ran

Cases	**Material**	**R (m)**	**t (cm)**	**L (m)**	**BF**
Case 1: Two	Material B	4.55	0.45	11.13	2.5
Case 2: Five	Material B	4.50	0.46	11.00	2.5
Case 3: Ten	Material B	3.50	0.20	10.01	3.2

Cases	**% Recycled**	**% Reman.**	**% Reused**
Case 1: Two	20.08%	63.35%	16.66%
Case 2: Five	73.52%	6.52%	20.05%
Case 3: Ten	51.84%	41.55%	6.70%

This result does not necessarily mean that it is the only optimal solution in the feasible region of the solution space. Although this illustration was based on simulated data in order to academically show the implementation of the framework, it reveals the added value that can be utilized by current designers today. Furthermore, it lays the groundwork for future work.

5. Summary and Outlook

This paper presents a framework that 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. A case study illustrating the relevance of the framework was also presented. The novelty comes from the utilization of the total life-cycle cost as the means to evaluate the sustainability of a component. In addition, the integration of the multi-generational view, or total life-cycle, with the component level assessment gives an unprecedented view on product design. The framework lays the foundation for future work that can include utilizing industry-relevant data in the evaluation of case-studies.

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