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A Framework for Sustainable Material Selection for Multi-Generational Components

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A FRAMEWORK FOR SUSTAINABLE MATERIAL SELECTION FOR MULTI-GENERATIONAL COMPONENTS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Mechanical Engineering
in the College of Engineering
at the University of Kentucky

By

Ryan Thomas Bradley

Lexington, Kentucky

Director: Dr. I.S. Jawahir, Professor of Mechanical Engineering

Lexington, Kentucky

2015

ABSTRACT OF THESIS

A FRAMEWORK FOR SUSTAINABLE MATERIAL SELECTION FOR MULTI-GENERATIONAL COMPONENTS

The early stages of a product's design are a critical time for decisions that impact the entire life-cycle cost. Product designers have mastered the first generation; however, they currently do not have the ability to know the impact of their decisions on the multi-generational view. This thesis aims at closing the gap between total life-cycle information and the traditional design process in order to harbor sustainable value creation among all stakeholders involved. A framework is presented that uses a combination of a life-cycle costing methodology and an evolutionary algorithm in order to achieve a sustainability assessment for a true multi-generational component. An illustration of the implementation of the framework shows the value to current engineering scenarios. A foundation is also laid for the overall future vision of this work to utilize proper databases and existing design tools to evaluate the overall sustainability and life-cycle cost of multi-generational components.

KEYWORDS: Sustainability, Sustainable Manufacturing, Material Selection, Product Design, Life-Cycle Costing

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July 22nd, 2015

A FRAMEWORK FOR SUSTAINABLE MATERIAL SELECTION FOR MULTI-GENERATIONAL COMPONENTS

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To my family

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Our society has been victimized by a culture that predates the Industrial Revolution. A culture that put profits above human life and the health of our environment. As the western world developed throughout the 20th Century, awareness of the social and environmental impacts that growing manufacturing and industrialization was putting on society began to propagate. In fact, many efforts were made and continue to be made in order to alleviate this burden of growth. However, these efforts have usually had only one aspect of improvement in mind. For example, the “Green” movement was completely focused on the environmental factor of industrialization with little or no consideration for the “unintended consequences” of that narrow focus. Today, sustainability comes to the forefront as being the all-encompassing ideology for total improvement. By definition, sustainability is improving the Triple Bottom Line (TBL). This improvement encompasses the economy, society, and the environment. Through this holistic approach, growth can still exist and even be improved while also meeting the needs of society and the environment. [1]

The less known, yet significant, application element of sustainability, is the idea of sustainable manufacturing. The concept is comprised of three core components: sustainable products, processes, and systems [2, 3]. The understanding of the integration of these core elements into product manufacturing is critical in the development of quantitative predictive models for sustainable product design and manufacturing [3].

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 maintain product and process quality with a total life-cycle cost benefit [1,2]. However, the primary principle that lies at the foundation of sustainable manufacturing is the idea of thinking with the end in mind, or more preferably, no end. This cradle-to-cradle approach or closed loop mentality, aims at integrating life-cycle data into the product design and manufacturing stages. As seen in Figure 1.1, the circular approach is an innovative way to look at product design. Designing a product from the beginning with multiple life-cycles in mind can create a significant advantage economically and can drive advancement in product and process technology.

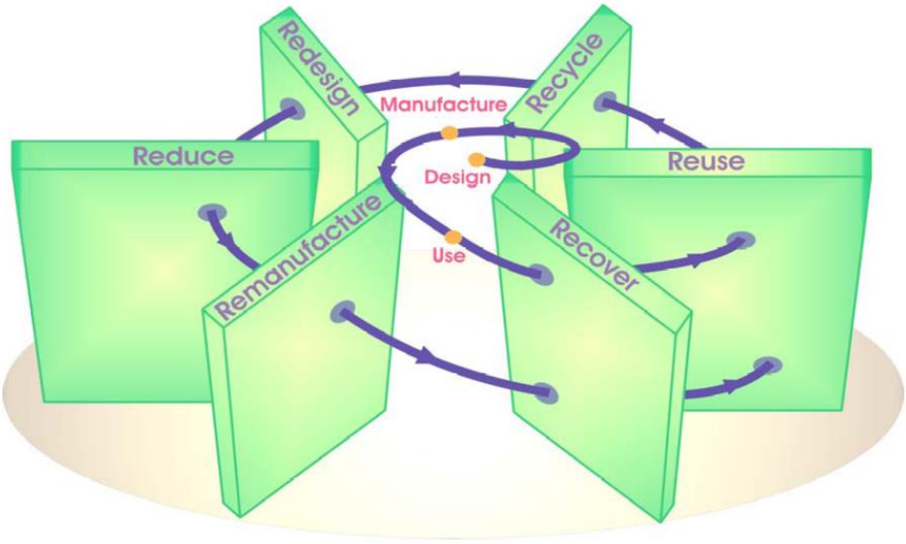


Figure 1.1: Multi-Life-Cycle products leading towards a closed loop. [3]

However, 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. In fact, Moreno et al [4] and Saravi et al. [5] estimate that 70 to 80 percent of the life-cycle costs of a product are determined by product designer's decisions made in stages prior to the conceptual design stage. Figure 1.2 shows the increased cost commitment of a product as a function of the time spent in the design cycle.

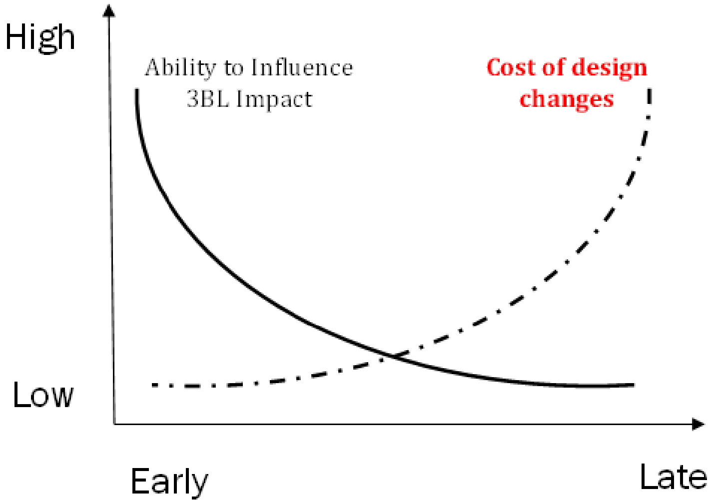


Figure 1.2: Design cycle cost commitment

This visually represents how design decisions like material selection can impact the total life-cycle of a product or component. For example, this is one reason why there has been considerable research done in the area of lightweight materials for consumer and commercial vehicles. This research is mostly driven by the desire to reduce the carbon footprint and the overall environmental impact. However, research in Soo et al. [6] has shown that short term reduction in environmental impact has consequently created a long term effect of increasing waste production. Therefore, there arises a need for the holistic assessment that sustainability concepts provide in order to aid in making these decisions.

While, LCA (Life-cycle Assessment) has been widely adopted as the most complete methodology to generate knowledge of environmental impact, its usage occurs at the latter stage of the design process [4]. This leaves product designers knowing very little about the total life-cycle triple-bottom-line impact of the most critical and costly design decisions. This deficiency is echoed in Saravi et al. [5] and Moldavska and Welo [7] and the claim is made that the challenge is grounded in making assessments objective, scientific, and internal to specific companies.

In addition, most sustainability assessments are done on the scale of the entire product, making it difficult to connect design decisions to the impact of the total life-cycle. Therefore, the need arises for a component level assessment that is independent of the product, yet is still able to tie to the impact of the product and the product's individual use. Donnelly et al. [8] show this to be beneficial for material selection decisions. In regards to the component level assessment of a product, this approach results in many other benefits. For example, a component level assessment can result in a simplified supply chain, simplifying the analysis to where costs can be explicitly calculated. In addition, this allows designers to be aware of the end-of-life of the various components. This gives an unprecedented ability to designers to make sustainable decisions in the early stages of the development of a product.

1.2 Proposal

Material selection is a critical decision for the overall life-cycle of a product. Material selection of a product or component gives substance to a design and bridges the gap from concept to reality [9]. That being said, the selection of a material can trap a manufacturer into astronomical unforeseen costs if not chosen correctly. With the numerous materials at society's fingertips today, the possibility for this to occur is greater than ever. In Figure 1.3, the evolution of the use of materials is mapped as a function of time. However, adequate consideration of the total life-cycle of these materials must be given in order to use these materials in the most efficient and most profitable way. That being said, this thesis proposes a framework for making sustainable material selection decisions for multi-generational components.

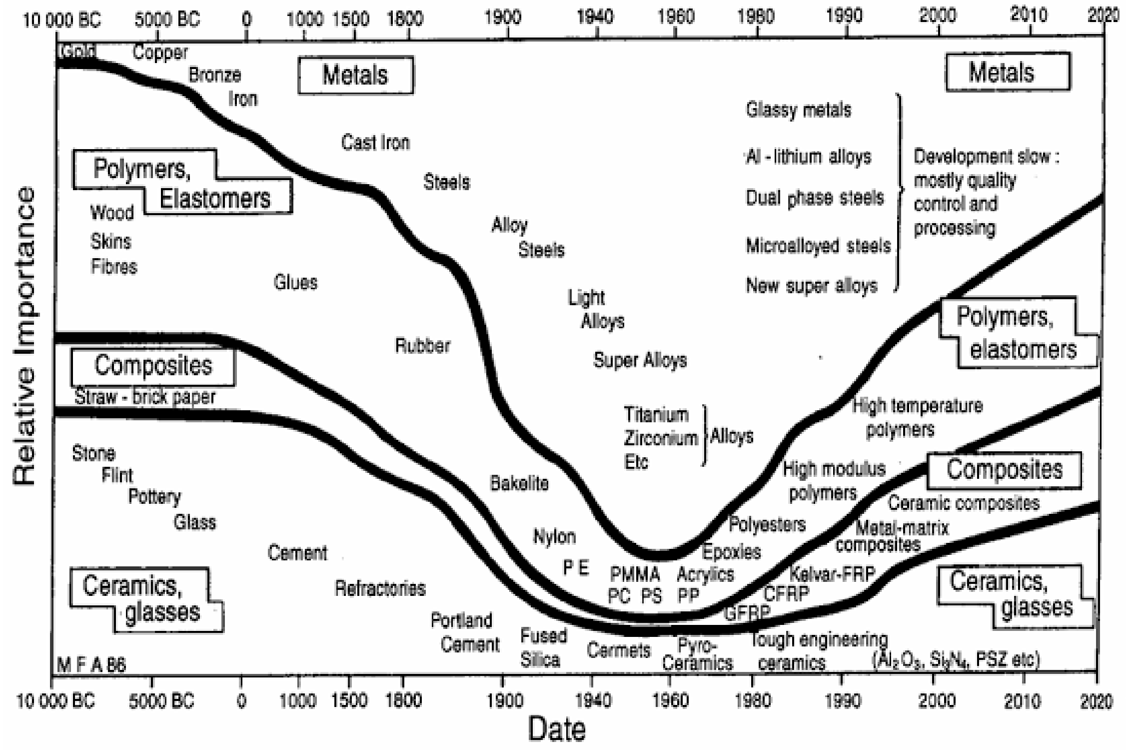


Figure 1.3 Evolution of engineering materials with time [9]

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. [10], this approach aims at being a driver for the innovation needed to reach 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 mentality not only targets the growing problem with depleting resources, but it reimagines what was once considered waste into an economic asset for future purposes. With this in mind, identifying the total life-cycle impact at an early design stage becomes of upmost importance.

To address this demand for earlier design integration, the framework is centered on an early entry ideology that allows designers to use life-cycle data in the material selection process before the conceptual design is finalized. This aids in the ability to create procedures for objectively evaluating these decisions.

As mentioned above, in an attempt to the make the framework as objective and quantitative as possible, a new framework is based upon the total life-cycle cost and is accompanied by a state-of-the-art evolutionary optimization algorithm. The objective nature of the life-cycle cost and the quantitative implementation of a TBL improvement by way of a mathematical algorithm provides an unprecedented approach to product design.

In addition, to satisfy the need of a component level assessment, the framework is built at the component level. That being said, 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, and is removed in one piece and is indivisible for the use in the overall product.

CHAPTER 2

LITERATURE REVIEW

2.1 The 6R Concept and the Circular Economy

2.1.1 The 6R Concept

The traditional application of the 3R concept (Reduce, Reuse, and Recycle) in design and manufacturing has often been featured in other ideology shifts in past history [11]. The “Lean” concept of the reduction of waste and the “Green” concept of the recycling of material both combine to form the 3R concept. However, this concept is short-sighted in that it follows a cradle-to-grave approach. It fails to recognize the post-use stage and the total life-cycle observance of the existence of multiple generations of use. ISM (The Institute of Sustainable Manufacturing) provides a more thorough methodology that is known as the 6R concept [1, 2]. This concept includes 3 post-use stage additions that are formally Recover, Redesign, and Remanufacturing. The inclusion of these aims at incorporating the “cradle-to-cradle” approach into the methodology. The resulting holistic view accounts for multiple generations and leads to the idea of a closed-loop material flow.

Since the formation of the 6R concept, there has been considerable research on its application to product design and manufacturing. Liew et al. [12] used aluminum beverage cans as a case study medium to apply the 6R concept for enhanced sustainability. The major elements of sustainable design were identified as shown in

Figure 2.1 and then applied specifically to the aluminum beverage can industry. The work showed great promise in improving the recycling process.

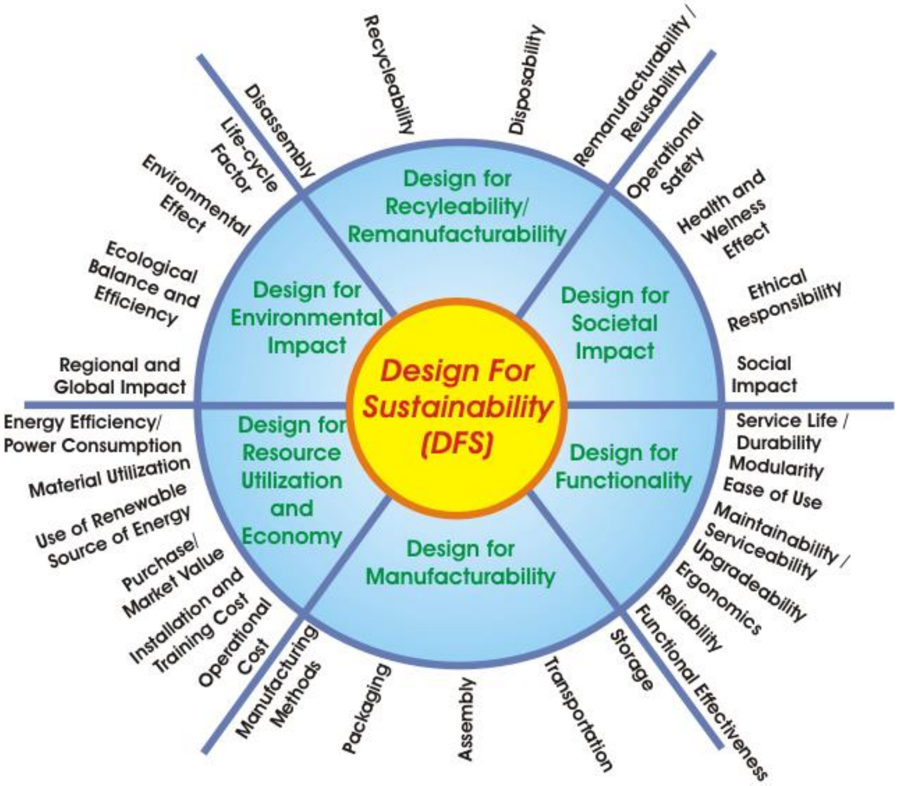


Figure 2.1: Elements that contribute to Design for Sustainability [1]

Ungureanu et al. [13] took the 6R elements and applied them to a different case study. In this case, aluminum auto body materials were reviewed and steel bodies were compared against aluminum bodies. The work used data published in literature to perform a comprehensive life-cycle analysis of both cases. The result showed that aluminum should be further reviewed as a potential replacement for steel in the future.

De Silva et al. [14] utilized the 6R elements in the development of a comprehensive methodology that evaluated the sustainability of a product at the design and development stage. The work continued on to apply the methodology to a case study involving consumer electronic products. The methodology took the 6 sub-elements that were seen in Figure 2.1 and formulated evaluation indices that combined to form an overall product index. The case study application to Lexmark Intl. Inc.'s products showed promise for being a comprehensive sustainability assessment.

Gupta et al. [15] showed the development of a set of metrics that comprehensively evaluate a product based on total life-cycle considerations. The paper identified the 4 stages of manufactured product as seen in Figure 2.2. These stages include Pre-Manufacturing (PM), Manufacturing (M), Use (U), and Post-Use (PU). The consideration of the total life-cycle gives the benefit of including areas that may be missed under the 3R approach.

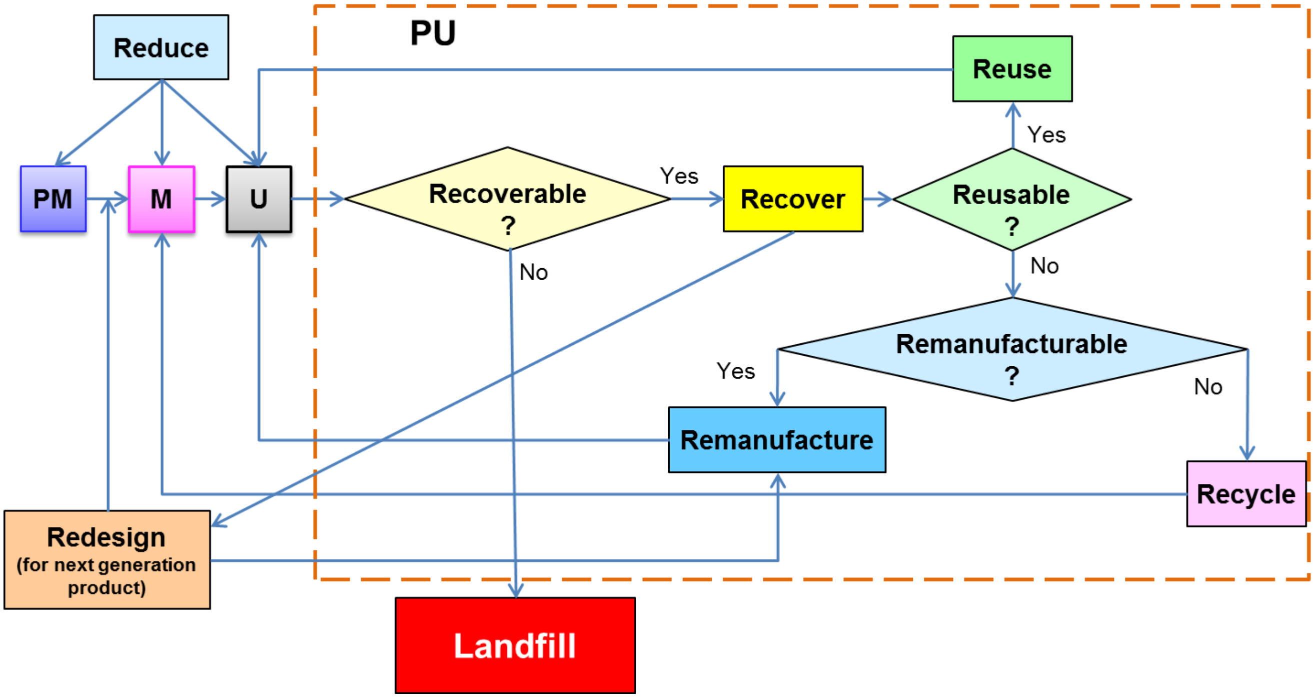


Figure 2.2: Total life-cycle flow [16]

Zhang et al. [16] expanded on the work by De Silva and established a product sustainability index that is based on metrics derived for the sub-elements as identified in

Figure 2.1. This mathematical and quantitative method gives the ability to apply the 6R concept to the assessment of an array of manufactured products.

2.1.2 The Circular Economy

The concept of a circular economy (CE) was first introduced by Zhu [17] in 1998 in a proposal that would be later adopted by the Chinese government in 2002 as a viable plan to alleviate growing resource depletion and pollution concerns [18]. Although not claimed to be an all-inclusive solution, scholars agree that CE could improve resource productivity and energy efficiency. However, from Yuan et al. [18], CE does not have an associated definition that clearly describes the intended application. In fact, CE is usually associated with material and energy flow, but is now making headway in being developed as an accepted economic strategy. The shift in CE becoming an economic strategy involves improving the TBL and not just focusing on environmental improvement. This shift in acceptance as seen in Yuan et al. [18], Yong [19], and Mathews and Tan [20] really brings the CE ideology to a point of synergy with the 6R Concept introduced by Dr. I.S. Jawahir and the Institute of Sustainable Manufacturing [1].

Yuan et al. [18] show that the conventional linear approach to economic development is unsustainable in China. The literature goes on to review the idea of CE and its implementation. In its implementation, CE occurs at three levels. The individual firm level, the regional level, and the province level. At the individual firm level, the firms are usually required to perform auditing of their manufacturing practices. As a part of this, local environmental agencies label the firms according to their environmental performance. At the regional level, developing an eco-friendly network of production systems is the primary objective. In fact, China has created eco-industrial parks where infrastructure and equipment is shared in order to implement CE at this level. At the third level, the focus shifts from a pure production standpoint and is refocused on both production and consumption.

Mathews and Tan [20] take a look at the CE implementation progress in China and compare it to more advanced countries in order to gage a form of performance. They go through each eco-industrial park, like the example shown in Figure 2.3 and then shows comparative parks in Denmark and in Australia. The literature then proposed a means to evaluate the success of such industrial parks. The underlying evaluation method is built on two primary ideas: 1.) the park should collectively improve the efficiency of the group of individual firms, and 2.) It must increase the profits of a single firm. Extrapolating this approach to the 6R concept, this is directly related to improving the TBL as seen in the 6R concept.

2.2 Material Selection in Design

2.2.1 The Design Process

Ashby, in his book *Material Selection in Mechanical Design* [21], defines the design process and makes the connection between it and the material selection decisions. When looking at product design, it all begins with a market need. This need is then formulated into a conceptual design. This beginning stage of the product is a definition of the need and a general direction of how to accommodate that need. During this stage, all design, material, and process alternatives are considered. Once there has been proper consideration given, the top concepts are then pushed to the embodiment design stage. At this stage, the design is broken down into manufacturable components and a preliminary range of materials is decided upon. Once this is completed, the design moves into the detailed design stage. At this time, components are finalized and the geometry and selected material is fully defined. This linear process can be visualized and is shown in Figure 2.3.

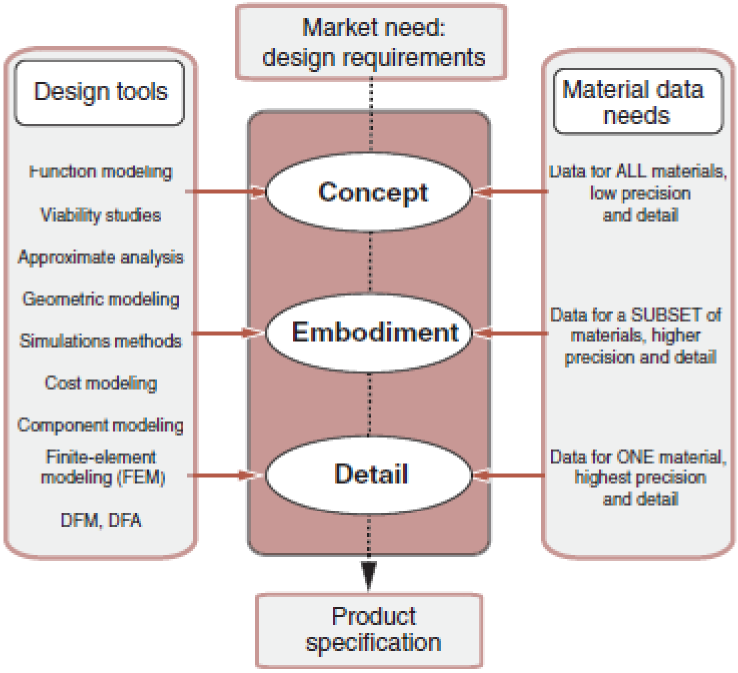


Figure 2.3: Design process and how the material selection process is integrated [21]

However, this linear relationship ignores the idea that the decisions made at one stage affect all stages that are downstream to that specific stage. Therefore, the design process, although recognizable as a linear process, can more accurately be described as a network of possibilities [21]. In other words, costs or consequences at the detail design stage that are related to decisions made at the conceptual design stage may go unnoticed until the cost of making the change or lack of time associated with approaching production makes the change impractical. This is why it is very important to provide designers with implications of cost at the early stages of the design process. This ensures upmost flexibility throughout the entire design process.

2.2.2 Current Practices of Material Selection

In Dixon and Poli [22] it is suggested that there is a four-level approach to materials selection in product design:

> Level 1 – Determine whether the part will be made from metal, plastic, ceramic, or composite.
>
> Level 2 – Determine which process will be used
>
> Level 3 – Select a subset of materials
>
> Level 4 – Select a specific material

However, what is more important than the levels themselves, is when in the design process the levels take place. Dixon and Poli [22] goes on to state that Level 1 and Level 2 are essential for the conceptual stage, while Level 3 is often reserved for the embodiment stage and Level 4 for the detail design stage. It is important to notice that Level 1 can considerably determine a huge chunk of the cost of the component. In fact, it becomes very important to provide designers with sufficient data during this design stage. When considering life-cycle data in this decision, Henriques et al. [23] states that making informed decisions are essential in the long-term impact of a product. Materials that are chosen based solely on initial cost and performance can result in higher production and/or use costs. Similarly, the lowest life-cycle cost material can result in higher environmental impacts. Therefore, it is important to consider life-cycle cost, while also ensuring the environmental impact and societal impact improve or remain constant. This is what will be implemented in the proposed methodology. Allwood and Cullen [24] claim that the business case with potential cost savings of switching materials is rather small. However, material selection can impact everything downstream of the product design phase. The total life-cycle approach is not addressed in this claim and therefor leaves room for improvement in developing a business case.

As far as methods of implementing a quantitative method for selection, Dixon and Poli [22] review two methods: the Cost per Unit Property Method, and the Weighted Property Index Method. In the cost per unit property method, the geometry is defined to be flexible about certain constraints. Ashby [21] uses this method when evaluating material selection decisions by using performance indices that are based on geometry and unit properties of the material in question. In the weighted property index method, a subjective method of weighting specific material properties occurs in order to determine the selected material. In the proposed methodology, a variation of the cost per unit property method will be implemented. The geometry will be allowed to be flexible and life-cycle cost, environmental impact, and performance will be determined per unit of material. This allows proper consideration of life-cycle data and the dynamic changes that are associated with choosing various materials.

2.3 Life-Cycle Costing

2.3.1 Background

In today's global marketplace it is increasingly important to tediously manage the cost of a product in order to remain competitive. In addition, it is just as important to track the environmental and societal costs in an increasingly conscious society. Consideration of the entire life-cycle has been shown to be effective in accomplishing both. Just as stated before, around 80% of the total cost of a product is influenced by decisions made in the early design stage. That being said, designers have the ability to make a dramatic cost impact by using this life-cycle approach. The concept, known as Life-Cycle Costing (LCC), was originally used as a procurement strategy by the Department of Defense. The idea was to find the optimal cost of acquisition, ownership, usage, and post-usage of a weapon system overtime. Following this, it was recognized that this concept could similarly be applied to product design. By considering production costs, usage costs, and post-usage costs, significant savings are at the fingertips of the product designer. In this section, current life-cycle costing models will be reviewed and then areas of improvement will be discussed [25, 26].

2.3.2 Current Models

In Asiedu and Gu [26], it is recognized that there exists three types of cost models: conceptual, analytical, and heuristic. Each has their own advantages and disadvantages. Conceptual models lack the ability to be applied to an in-depth analysis, but they 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 does not guarantee an optimal solution.

From Dhillon's book [27] *Life-cycle Costing for Engineers,* six generic life-cycle cost models are presented. For the purposes of this thesis, four will be reviewed to be able to see the progression. In addition, Dhillon discusses several application specific models that will be briefly discussed.

The first model that will be reviewed is shown in Equation (2.1) [27].

$$LCC = RC + NRC \tag{2.1}$$

where,

LCC is component or system life-cycle cost,

RC is recurring cost, and

NRC is nonrecurring cost.

The model is further broken down to specifically describe costs associated in both the recurring and nonrecurring costs. It is important to note that this model is more applicable to a procured system rather than a designed product.

The second model is a similar model but is broken down into three parts rather than two. This model is shown in Equation (2.2) [27].

$$LCC = C_1 + C_2 + C_3 \tag{2.2}$$

where,

LCC is component or system life-cycle cost,

C_1 is acquisition cost,

C_2 is initial logistics, and

C_3 is recurring cost.

This model is very similar to the first one in that it is more applicable to procured systems. The main difference between the two arises in the initial logistic costs. This is an area that is not considered in the first model.

The third model is one that was developed by the U.S. Navy and was used to calculate the life-cycle cost of weapon systems. It is shown in Equation (2.3) [27, 30, 31].

$$LCC = C_1 + C_2 + C_3 + C_4 + C_5 \tag{2.3}$$

where,

LCC is system life-cycle cost,

C_1 is research and development cost,

C_2 is associated system costs,

C_3 is investment cost,

C_4 is termination cost, and

C_5 is operating and support cost.

In this model, the consideration for the end-of-life is first seen. The termination cost is a result of decommissioning weapons.

Moving on to the fourth model, this is another one that specifically addresses the post-use phase. It can be seen in Equation (2.4) [27].

$$LCC = C_{rd} + C_{pc} + C_{os} + C_{rt} \tag{2.4}$$

where,

LCC is life-cycle cost,

C_{rd} is research and development cost,

C_{pc} is production and construction cost,

C_{os} is operations and support cost, and

C_{rt} is retirement and disposal cost.

where, the retirement and disposal cost is defined by Equation (2.5) [27].

$$C_{rt} = C_{ur} + [\theta K(C_{id} - r)] \tag{2.5}$$

where,

C_{rt} is retirement and disposal cost,

θ is a condemnation factor,

K is total number of maintenance actions,

C_{ur} is the ultimate retirement cost,

C_{id} is the item disposal cost, and

r is the reclamation value.

The end-of-life consideration in this model is one that can be used in consideration of the total life-cycle in order to develop a more comprehensive life-cycle cost model. As mentioned above, Dhillon also presents several specific life-cycle cost models for a given application. The literature covers models intended for healthcare facilities, weapon systems, and even software. Each follow a similar structure as the models that were shown above, but their subcategories are made specific to that particular product or system. These specific models reflect a more detailed analysis and cost accounting of a given system. The downside is that a model must be created for each individual component [27].

2.3.3 Areas of Improvement

Now that a brief background on life-cycle costing and some of the current models were discussed, it is now time to address the deficiencies in the current models. Asiedu and Gu [26] 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. [5] also suggest that there is need for an early design stage cost model that allow product designers to make more informed decisions.

Prox [28] suggests that life-cycle costing be spread to the entire supply chain rather than be contained within the boundaries of a single company. To do this, the literature suggests that associated downstream and upstream suppliers collaborate and share life-cycle information in order to identify possible areas of improvement when looking at the total life-cycle of a product.

2.4 Multi-Objective Optimization

2.4.1 Background

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. For a review of the various methods that can be used, Deb [29] summarizes a few of the most common methods.

The first two methods involve adapting the MO problem to be able to be solved as a single objective problem. In the first method, the weighted-sum approach, takes the objectives and merges them into one objective by pre-applying user-specified weights to the objectives. This is a subjective approach, since there is not a deterministic set of weighting values. That being said, this can be mitigated to a point by normalizing the objectives prior to applying the weights [29].

The second method, the e-constraint method, aims at fixing a common problem with the weighted-sum approach. With the weighted-sum approach, it cannot solve problems that have a non-convex solution space. Therefore, the second method takes all of the objectives and only chooses to keep a single objective for the optimization. The other objectives are then enforced by clarifying user-specified constraints. Unfortunately, depending on the enforced constraints, there may not be a feasible solution [29].

In addition to these “classical” methods there also exists methods known as evolutionary multi-objective optimization (EMO) and particle swarm optimization (PSO). The EMO that will be discussed is a high level genetic algorithm (GA).

In a GA, a population of chromosomes that it is made up of a specific set of variables or genes. These chromosomes evolve over a user-specified number of generations by the way of crossover or mutation. In crossover, it is a resemblance of mating in that the parent chromosomes are joined together to form the new generation chromosomes. The idea behind this operation is based off the “survival-of-the-fittest” concept seen in the theory of evolution. The more generations that pass, the more “fit” the subsequent generations should be. In mutation, randomization is introduced into the chromosomes. This aids in keeping the solution from converging on the local optima [30].

Founded by James Kennedy and Russell Eberhart, a PSO is a little different than EMO. The primary difference between it and EMO is that in PSO the entire population survives from the beginning until the end. In PSO, there exists a swarm of particles instead of a population of chromosomes. These particles are spread throughout the solution space and the objective functions are then calculated. Then a “velocity” is applied to each particle in order for each particle to move to a new location in the solution space. The objectives are then recalculated in order to determine if the new position is more optimal than the previous. If it is, that location is used to adjust the velocity for the subsequent generation. The idea is that over time the swarm of particles will converge on a common optima in the solution space [31].

2.4.2 MO in Material Selection

Like mentioned above, decisions that require multiple considerations must use MO in the optimization process. Material selection often falls into this category. Often when designing a product, the material must satisfy minimum performance considerations, be lightweight, be recyclable, and/or minimize cost. That being said, there has been considerable research done in this field, and it mostly involves the use of EMO. For example, Sakundarini et al. [30] use a GA in order in formulating a methodology for material selection of high recyclability. A case study was performed that showed the proposed method was able to generate an optimal solution. In Coello and Becerra [32] MO and its application to the field of material science is reviewed. It states that MO has been used in order to determine things like material alloy percentages and processing characteristics. Coello and Becerra [32] also note that GA is the most widely used algorithm in the field, but does recognize PSO has a potential alternative. PSO’s lack of adoption is more likely due to age of the algorithm than to the inability to perform. That being said, both have the ability to be implemented into the material selection decision.

CHAPTER 3

METHODOLOGY AND FRAMEWORK

Since the needs were defined by reviewing past work in the previous chapter, this chapter focuses on presenting a framework for a material selection process that considers the total life-cycle and multiple generations of a component. A flowchart that shows an overview of the proposed framework is shown in Figure 3.1. 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. Throughout this chapter the framework for the life-cycle cost model will first be discussed, followed by the framework for the optimization algorithm, and then followed by the software prototype and platform.

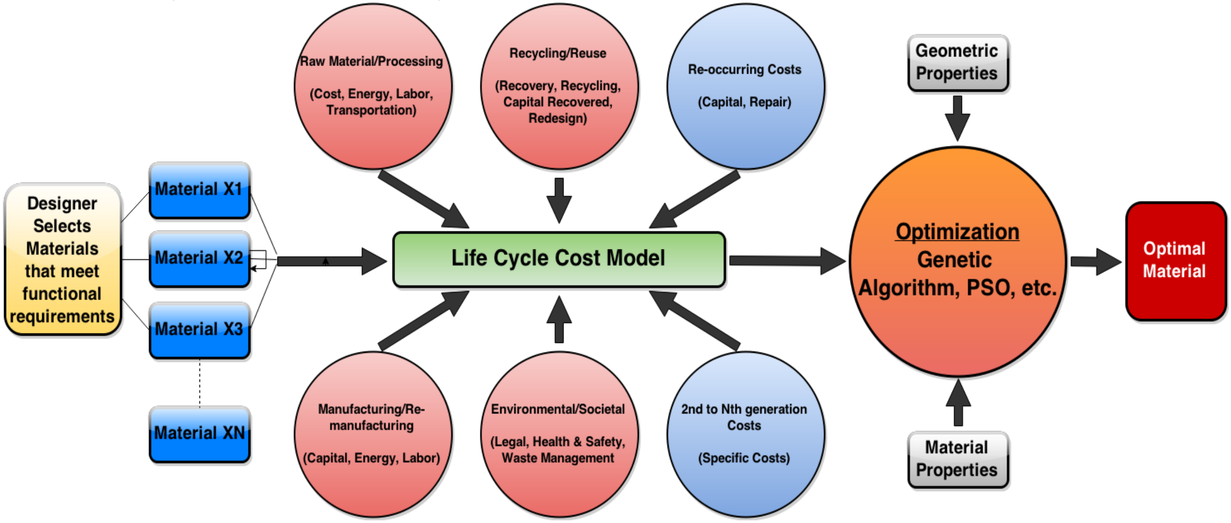


Figure 3.1: Overview of the proposed framework

3.1 Life-Cycle Cost Model Framework

The life-cycle cost model that will proposed in this section is intended to satisfy two main criteria: 1) Consider the entire life-cycle by considering multiple generations, and 2) Be implementable in the conceptual design stage. This section will discuss the methodology behind multiple generations and then reveal the proposed model.

3.1.1 Consideration of Multiple Generations

As mentioned multiple times before, designers tend to only take into account a single generation of a product when making design decisions such as material selection. However, it has been determined that this no longer satisfactory in order to accurately quantify the life-cycle impact of these early design decisions. In order for this to be possible, the entire life-cycle must be taken into consideration by viewing the components as multi-generational. To be able to extend the view from single generation to multiple generations, the first generation must be completely understood. Shown in Figure 3.2 is a visual of the ideal material flow over a single generation.

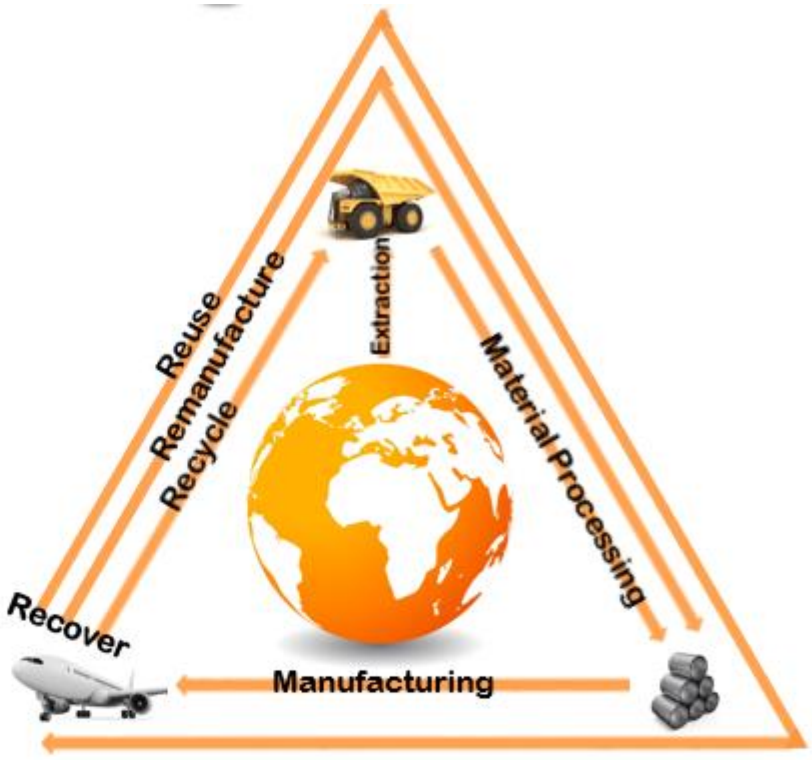


Figure 3.2: Ideal material flow over a single generation

In this figure, the circular nature of material flow is encapsulated by utilizing the 6R concept. 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 doesn’t show is subsequent generations of product during the Redesign phase. In addition, since this is the ideal material flow, Figure 3.2 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. Therefore, to illustrate the multi-generational view of material flow, one must include the redesign stage. Shown in Figure 3.3, the single generation view of material flow is extrapolated to a multiple generational view.

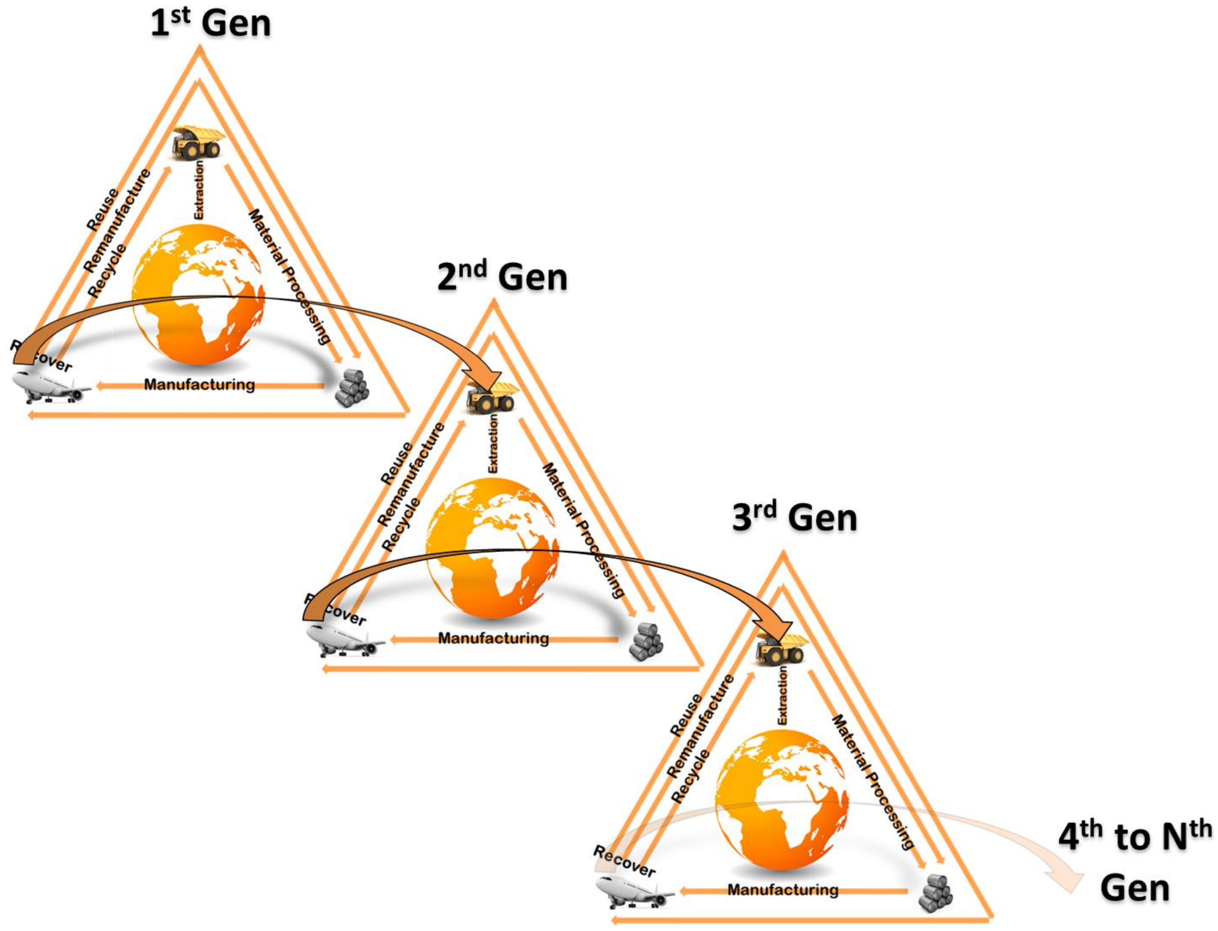


Figure 3.3: Multi-Generational view of material flow

In this figure, the Redesign stage is well visualized. This helical pattern of moving from one generation to the next is supposed to represent utilizing the material from one generation in the next generation of products. Although the helical pattern is not circular, it still represents a circular economy in that the used material is accounted for and allocated appropriately to minimize the occurrence of waste. This multiple generation consideration is what the proposed life-cycle cost model tries to implement.

3.1.2 The Proposed Model

As seen in Figure 3.4, 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 and make independent decisions; however, as seen in Rivera et al. [33] their decisions significantly affect one another. Breaking the Cost into these two areas provided two significant advantages. The first is that 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

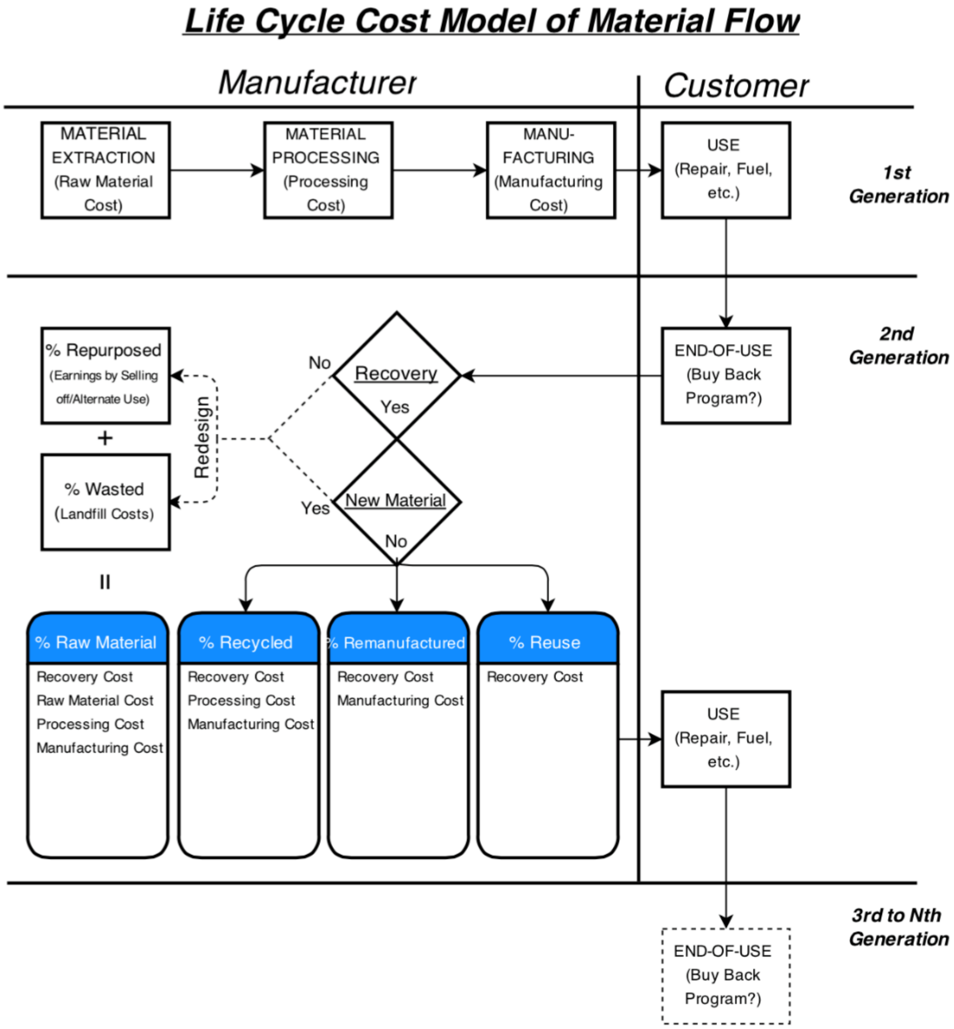


Figure 3.4: Proposed life-cycle cost model

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.

First, the presence of the differing stakeholders must 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, it can be described by Equation (3.1).

$$TLCC = C_{MFG} + C_{CUST} \tag{3.1}$$

where,

$TLCC$ is the total life-cycle cost,

C_{MFG} is the cost to the manufacturer, and

C_{CUST} is the cost to the customer.

This term “total life-cycle cost” may seem ambiguous and even unimportant from the singular perspective of the manufacturer or customer. That being said, 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, the each of these two costs can be described in much more detail. This can be seen in Equations (3.2) and (3.3). In these equations, the costs are only showed for the first generation. Later equations will address the multi-generational component of the model.

$$C_{MFG} = RM + \sum_{i=1}^{N_1} PM_i + \sum_{i=1}^{N_2} RE_i + \sum_{i=1}^{N_3} RRR_i + \sum_{i=1}^{N_4} ES_i + \sum_{i=1}^{N_N} Z_i \tag{3.2}$$

where,

C_{MFG} is the cost to the manufacturer,

RM is the raw material cost,

PM_i is the processing and manufacturing cost,

RE_i is the recovery cost,

RRR_i is the cost associated with remanufacturing, recycling, and reusing,

ES_i is the cost associated with environmental and societal relations,

Z_i is costs that are specific to a given application and outside the generic model, and

N_{1-N} is the number of subcategories within the major cost categories.

$$C_{CUST} = AC + \sum_{i=1}^{N_1} U_i + \sum_{i=1}^{N_2} M_i + \sum_{i=1}^{N_N} Z_i \tag{3.3}$$

where,

C_{CUST} is the cost to the customer,

AC is the acquisition cost,

U_i is the usage cost,

M_i is the maintenance cost,

Z_i are costs that are specific to a given application and outside the generic model, and

N_{1-N} is the number of subcategories within the major cost categories.

The cost variables that have the indexing variable indicate that they can be broken down even more specifically to their subcategories. At this level, it begins to become specific to the given application, but for the purposes of this thesis a generic view of these individual cost categories will be shown in Equations (3.4) through (3.9).

$$\sum_{i=1}^{N_1} PM_i = EC + LC + TC + CC + MC + Z_i \tag{3.4}$$

where,

PM_i is the processing and manufacturing cost,

EC is the energy cost,

LC is the labor cost,

TC is the transportation cost,

CC is the capital cost of processing and manufacturing equipment,

MC is the material cost excluding working material, and

Z_i are costs that are specific to a given application and outside the generic model

In this equation, the costs all relate to a specific material. Therefore, the costs will not always be explicitly known and instead must be calculated. For example, the transportation costs of one material and another material may be constant unless the material of the component is tied to how the transportation is done. In other words, Material A may require more volume to satisfy a certain application than Material B. Therefore, it may require more truckloads for transportation than Material B. At the same time, each truckload of Material B may be lighter than Material A. In that case, the fuel used during transportation, freight fees and taxes, etc. may be much higher for Material A than for Material B. These are the types of considerations that must be taken into account for this life-cycle cost model.

$$\sum_{i=1}^{N_2} RE_i = EC + LC + TC + LOC + Z_i \tag{3.5}$$

where,

RE_i is the recovery cost,

EC is the energy cost,

LC is the labor cost,

TC is the transportation cost,

LOC is the logistical cost, and

Z_i are costs that are specific to a given application and outside the generic model.

In this equation, the term “logistical cost” may seem ambiguous. This is really intended to serve as the umbrella term for any program that a manufacturer may implement in order to push for the recovery of products. An example of this can be seen in the printer manufacturing industry. The manufacturer produces toner cartridges for the use in their printers, and then they issue a return program where the cartridge is taken back by the manufacturer and is remanufactured in order to be reused [34]. Even though these programs are obviously beneficial to the manufacturer, they have associated costs that must be accounted for in this model.

$$\sum_{i=1}^{N_3} RRR_i = (x_1)\sum_{i=1}^{N_1} P_i + (x_1 + x_2)\sum_{i=1}^{N_1} RMC_i + TC - CR + Z_i \tag{3.6}$$

where,

RRR_i is the cost associated with remanufacturing, recycling, and reusing,

P_i is the material processing cost,

RMC_i is the remanufacturing cost,

TC is the transportation cost,

CR is the capital recovered as compared to raw material cost,

x_1 is the percent of material recycled,

x_2 is the percent of component material that is remanufactured, and

Z_i are costs that are specific to a given application and outside the generic model.

This equation has a different appearance than the other questions. For one, it has the occurrence of percentage factors that multiple components of the equation. These percentages represent the amount of material that is placed into each of the streams post-recovery. Each of these streams have differing costs and the percentage aspect allows the cost of these streams to be calculated based on the initial manufacturing and processing costs. In this case, the material that has been recycled will incur costs that require it to be reprocessed and then remanufactured. Material that is placed into the remanufacturing stream will only incur the costs associated with being remanufactured. Finally, the material that is being reused is assumed to not incur either processing or manufacturing costs.

In addition to the percentage factors, the existence of the subtraction of a cost component is seen in this equation. This is something that is unique in comparison to the other equations. What this represents is the recovered capital cost as compared to the use of raw material. This is made on the direct assumption that the use of recycled materials is cheaper than the use of raw material. This is obviously not always the case, and the equation will adjust accordingly if perhaps a recycled material was being used that was more costly than its associated raw material.

$$\sum_{i=1}^{N_4} ES_i = LEC + WMC + HSC + LOP + Z_i \tag{3.7}$$

where,

ES_i is the cost associated with environmental and societal relations,

LEC is the legal costs,

WMC is the waste management cost,

HSC is the health and safety liability costs,

LOP is the loss of profit from tarnished public image, and

Z_i are costs that are specific to a given application and outside the generic model.

These costs tend to be the ones that are the hardest to objectively evaluate without the use of historic data. However, they have to be considered and may require some creativity in order to provide an accurate representation. An example of this type of costing consideration can be described by the infamous Ford Pinto case. Although Ford's motives were not moral in nature, their costing strategy was a brilliant example of quantifying design decision impacts on health and safety liabilities [35]. Ford was able to calculate the cost of settlements for their design mistakes based on a significant probability study. Although Ford used it differently than what any human being would hope, it provides an example of how this can aid in the ability to perform in-depth costing analysis to evaluate design decisions.

$$\sum_{i=1}^{N_1} U_i = FC + OCC + Z_i \tag{3.8}$$

where,

U_i is the usage cost,

FC is the fuel cost,

OCC is the operational consumable cost, and

Z_i are costs that are specific to a given application and outside the generic model.

The usage cost is highly dependent upon the given application. Many components may not have a usage cost. With other components, the usage cost may dominate all other costs. For example, a component that is associated with any type of vehicle, there will be some type of usage cost associated. However, this usage cost may not be directly related to the material used itself. The same kind of logic applies here as did with the transportation cost in Equation (3.4). More specifically, a hypothetical situation could arise in which Component A's material weighs 30% more that Component B's material, but Component B's material requires a regular application of a protective coating. In this case, the fuel costs are going to be higher for Component A, but the OCC costs will be higher for Component B.

$$\sum_{i=1}^{N_2} M_i = CM + DR + Z_i \tag{3.9}$$

where,

M_i is the maintenance cost,

CM is the common scheduled maintenance cost,

DR is the damage repair cost, and

Z_i are costs that are specific to a given application and outside the generic model.

This equation is similar to that of Equation (3.8) in that it is highly dependent upon the given application. However, the damage repair cost needs to be directly defined. This cost can be directly related to chosen material, but may require a probability study in order to be evaluated. For example, the use of Material A may result in a damage rate of 5% of the time and cause damage that is 20% more than the cost of damage that arises from the use of Material B. However, Material B may result in a damage rate of 6.5% of the time. This results in a difference in occurrence of 30%. Therefore, it turns out that Material A actually holds a lower cost in regards to the damage repair cost.

Now, that the model has been showed in detail for the first generation, it must be extended to the 2nd-Nth generations. Seen in Equation (3.10) is the multi-generational version of the manufacturer cost equation.

$$C_{MFG} = G\left[\left(\frac{1}{G} + (1 - x_4)\right)\left(RM + \sum_{i=1}^{N_1} PM_i\right) + x_4 \sum_{i=1}^{N_2} RE_i + (x_4 - x_3) \sum_{i=1}^{N_3} RRR_i + \sum_{i=1}^{N_4} ES_i + \sum_{i=1}^{N_N} Z_i\right] \tag{3.10}$$

where,

C_{MFG} is the cost to the manufacturer,

RM is the raw material cost,

PM_i is the processing and manufacturing cost,

RE_i is the recovery cost,

RRR_i is the cost associated with remanufacturing, recycling, and reusing,

ES_i is the cost associated with environmental and societal relations,

Z_i is costs that are specific to a given application and outside the generic model,

N_{1-N} is the number of subcategories within the major cost categories,

G is the number of generations,

x_3 is the percentage of material reused, and

x_4 is the percentage of material that is recoverable.

The obvious change in this equation is an existence of a term to account for multiple generations. However, it is not as simple as a multiplication factor. In fact, there are several constants that have been introduced in order to represent decisions made throughout the life-cycle. To be more specific, 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 also x_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.

Now, that the manufacturer equation has been analyzed, the customer equation must also be equivalently extended to a multi-generational version. This is seen in Equation (3.11).

$$C_{CUST} = G\left(\left(\frac{1}{G} + I\right)(C_{MFG} * K) + \sum_{i=1}^{N_1} U_i + \sum_{i=1}^{N_2} M_i + \sum_{i=1}^{N_N} Z_i\right) \tag{3.11}$$

where,

C_{CUST} is the cost to the customer,

AC is the acquisition cost,

U_i is the usage cost,

M_i is the maintenance cost,

Z_i are costs that are specific to a given application and outside the generic model,

N_{1-N} is the number of subcategories within the major cost categories,

G is the number of generations,

K is the constant of profitability, and

I is the incentivized cost. This may or may not be present.

This equation is very similar to that of the manufacturer equation. However, the major difference occurs with the presence of I. This factor is different than the multipliers used in the manufacturer equation. In fact, it can be seen that I is only applied to the acquisition cost. What this factor is supposed to represent is the presence of an incentivized cost or reimbursement for returning the previous generation component. A good example of this is shown through the electronics industry. A lot of 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 [36].

3.2 Optimization Framework

The optimization algorithm chosen to be implemented into the sustainable material selection process 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. Throughout this section, an overview of the algorithm will be discusses, then the objectives will be reviewed, and lastly the constraints will be discussed.

3.2.1 Overview of the Algorithm

For the GA, it is important to discuss the structure of the chromosome being utilized for optimization. Shown in Figure 3.5 is the generic chromosome structure for the algorithm.

M_1	M_2	$\cdots$	M_N	G_1	G_2	$\cdots$	G_N

Figure 3.5: Chromosome Structure for GA

Shown in this figure, the G present in the chromosome represents the geometric properties of the component. The specificity and number of them depend upon the

$$M_i = \begin{Bmatrix} E \\ BHN \\ \rho \\ \sigma_f \\ \vdots \\ C_{CUST} \\ C_{MFG} \end{Bmatrix}_i$$

Figure 3.6: Material Properties Vector

component being evaluated and the designer’s input. The M represents a certain candidate material that is being evaluated. The number of them present in the chromosome depend upon how many candidate materials are under evaluation. These are binary and indicate which set of material properties are to be used for the calculation of objective functions and constraints. An example of the material property array can be seen in Figure 3.6.

Seen in this figure are various material properties along with a couple familiar cost components. The material properties are variable and are dependent upon the constraints and objective functions used. The cost variables, on the other hand, are a product of what was calculated in the life-cycle cost model. This costs are per unit of material, therefore making them independent of the design and geometry.

As far as the specific characteristics used in the GA that must be determined by the user, they include the population size, the crossover rate, the mutation rate, and the stopping criteria. It is recommended that the population size be 100 or greater, the mutation rate be 5% or less, and the stopping criteria be 500 generations or more.

3.2.2 Objective Functions

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 anything 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. This first type of objective function can be mathematically described generically as in Equation (3.12)

$$P(i) = f(M_i, G_i) \tag{3.12}$$

In this generic equation, the objective function is a function of the material properties of the candidate material and the geometry of 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. Seen in Equation (3.13), it is a function of the candidate material's properties, geometry of the material and the manufacturer life-cycle cost.

$$C = f(M_i, G_i, C_{MFG}) \tag{3.13}$$

This function represents the life-cycle cost to the manufacturer of the component and is intended to be minimized. However, it may be noticed that the customer side of the life-cycle cost cannot be found in this objective function. The reason why is because this part of the life-cycle cost is actually enforced through the use of constraints as seen in the next section.

3.2.3 Constraints

For this framework, there exists three different types of constraints that are used in the implementation of the GA. These include the triple bottom line relationships, the user-defined relationships, and the user-defined geometric constraints.

For the TBL relationships, there are 4 different enforced relationships that are intended to be used to ensure there is improvement in the TBL. 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. Although, the manufacturer does not incur the cost that the customer takes on, it is still an important consideration as seen in Rivera et al. [33]. This relationship can mathematically formulated as shown in Equation (3.14).

$$-K(C_{MFG_{Current}} - C_{MFG_{Baseline}}) \geq \ C_{CUST_{Current}} - C_{CUST_{Baseline}} \tag{3.14}$$

here,

$C_{MFG_{Current}}$ is the cost to the manufacturer for the evaluated component,

$C_{MFG_{Baseline}}$ is the baseline cost to the manufacturer from a previous generation or user-defined,

$C_{CUST_{Current}}$ is the cost of ownership to the customer for the evaluated component,

$C_{CUST_{Current}}$ is the baseline cost to the customer from a previous generation or user-defined, and

K is the profitability constant.

What this equation does is ensure that the change in acquisition cost to the customer from the baseline, this being a previous generation or user-defined, is never compromised for the total cost of customer ownership. In other words, for material selection or substitution to take place, the reduction in manufacturing cost cannot be less that the total increase in the cost of use. This is made under the primary assumption that the manufacturer will pass the cost savings or hikes on to the customer. Since this isn’t strictly linear, the profitability constant was introduced to reflect the manufacturer still being profitable at all times.

The next relationship looks at ensuring the environmental impact improvement of the component. This relationship can be seen in Equation (3.15).

$$EI_{New}V_{New} \leq EI_{Baseline}V_{Baseline} \tag{3.15}$$

where,

EI_{New} is the environmental impact of the new generation component per unit of material,

V_{New} is the material volume of the new generation component,

EI_{Old} is the environmental impact of the baseline or previous generation per unit of material,

V_{Old} is the material volume of the baseline or previous generation.

This equation utilizes the environmental impact of the candidate material that is present in the material property array and calculates as a unit of the candidate material. This constraint then holds it to the fact that the total environmental impact is a function of varying geometry.

The third relationship takes the same form in that it's only difference is that the environmental impact is substituted for societal impact. This relationship is shown in Equation (3.16).

$$SI_{New}V_{New} \leq SI_{Baseline}V_{Baseline} \tag{3.16}$$

where,

SI_{New} is the societal impact of the new generation component per unit of material,

V_{New} is the material volume of the new generation component,

SI_{Old} is the societal impact of the baseline or previous generation per unit of material,

V_{Old} is the material volume of the baseline or previous generation.

This equation, like Equation (3.15), utilizes the societal impact of the candidate material that is present in the material property array and calculates it as a unit of the candidate material. This constraint then holds it to the fact that the total societal impact is a function of varying geometry.

The last TBL relationship, shown in Equation (3.17), involves ensuring the functional performance meets the failure criteria set forth by the designer.

$$Criteria\ Set\ Point \leq\ f(M_i, G_i) \tag{3.17}$$

This relationship takes the objective functions and enforces the criteria set by the way of a constraint. This can shape as setting a bottom line or top line depending upon the objective function in question.

Now, looking at the user-defined relationships these are completely dependent upon the component in question. Since the generic model cannot describe all components in detail and remain flexible, these user-defined relationships are reserved for the injection of specificity. The user defined relationship can generically be seen in Equation (3.18).

$$g(M_i, G_i, C_{MFG}, C_{CUST})$$

$$h(M_i, G_i, C_{MFG}, C_{CUST})$$

$$\ldots$$

$$Nth(M_i, G_i, C_{MFG}, C_{CUST}) \tag{3.18}$$

The final type of constraint that is present in this framework is the user-defined geometric constraint. This is actually quite straightforward in that it is a limit system enforced upon the various geometric dimensions of the component. However, the idea is that the designer should not constrain the geometry too strictly in order to leave the model as flexible as possible. That being said, a generic geometric constraint can be seen in Equation (3.19).

$$Lower\ Limit\ <\ G_i\ <\ Upper\ Limit \tag{3.19}$$

Now, that the objective functions and the constraints have been reviewed in detail, next a summary will be given to shown the framework more completely.

3.2.4 Summary of Optimization Framework

Shown in this section is a summary of the objectives and constraints that formulate the generic optimization model,

where,

C_{CUST}	Life-cycle Cost to Customer
C_{MFG}	Life-cycle Cost to Manufacturer
$M_i(E, \rho, \sigma, Machinability\ Rating, BHN, \ldots etc)$	Material Properties Index
$G_i(r, t, L, h, w, \ldots etc)$	Geometric Properties Index

<u>Objectives:</u>

Type 1 - Maximize/Minimize Performance and Functionality

$f(M_i, G_i)$

(Examples: Weight, Fatigue Life, Buckling, etc.)

Type 2 - Minimize Total Life-Cycle Cost

$f(M_i, G_i, C_{MFG})$

<u>Subject to:</u>

Type 1 - Customer/Manufacturer Relationship

$$-K(C_{MFG_{Current}} - C_{MFG_{Baseline}}) \geq C_{CUST_{Current}} - C_{CUST_{Baseline}}$$

Environmental Performance Relationship

$$EI_{New}V_{New} \leq EI_{Baseline}V_{Baseline}$$

Societal Performance Relationship

$$SI_{New}V_{New} \leq SI_{Baseline}V_{Baseline}$$

Functional Performance Limit

$$Criteria\ Set\ Point \leq f(M_i, G_i)$$

Type 2 - User-Defined Relationships

$$g(M_i, G_i, C_{MFG}, C_{CUST})$$

$$h(M_i, G_i, C_{MFG}, C_{CUST})$$

$$\dots$$

$$Nth(M_i, G_i, C_{MFG}, C_{CUST})$$

Type 3 - Geometric Constraints

$$Lower\ Limit < G_i < Upper\ Limit$$

3.3 Procedure and Platform

3.3.1 Procedural View

A visualization of how the framework is implemented can be seen in Figure 3.7.

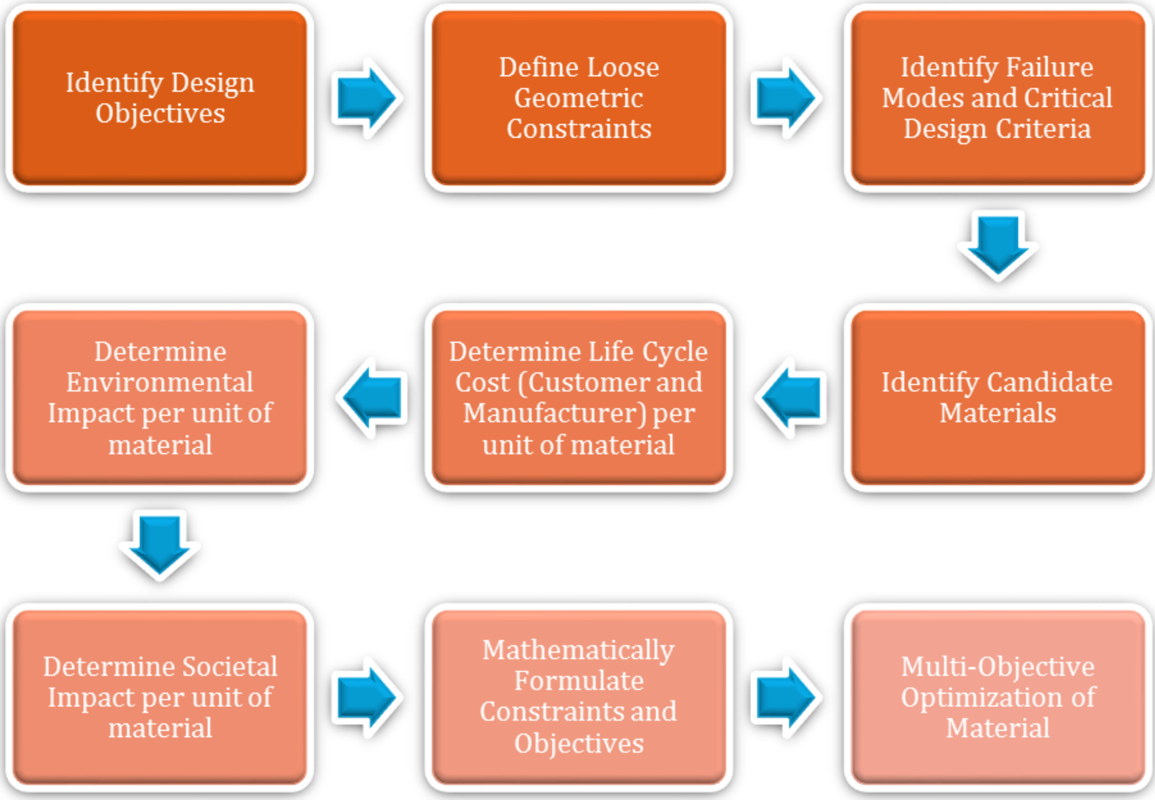
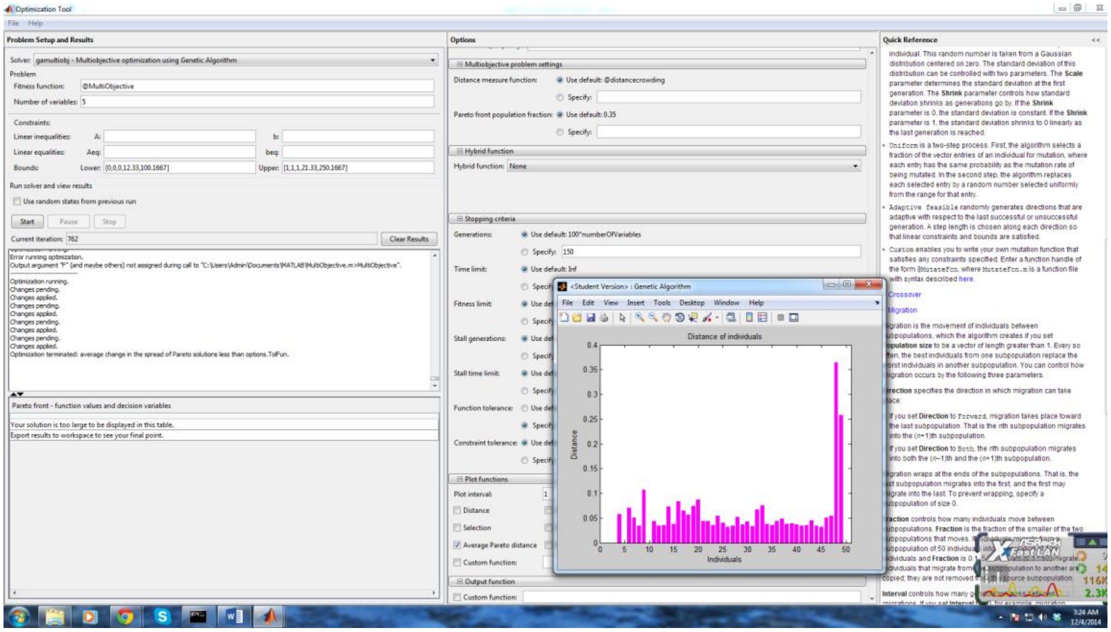


Figure 3.7: Procedural view of implementation of the framework

This is the end-to-end procedure of the framework and can be applied to any component and material selection decision. As far as the implementation of the GA, the platform used will be discussed in the next section.

3.3.2 Software Platform

To solve this problem, MATLAB's Global Optimization Toolbox was used as the platform in order to use the multi-objective genetic algorithm solver [37]. Since MATLAB minimizes the objective functions, a little creativity was needed in order to adapt the maximization fitness functions. Also, MATLAB doesn’t easily support binary constraints without extensive change to the backend of the GA solver [3]. Therefore, original code had to be constructed in order to retrofit the global optimization toolbox to the type of problem that was trying to be solved. Shown in Figure 3.8 is the GA solver GUI (Graphical User Interface).



Solver: gamultiobj - Multiobjective optimization using Genetic Algorithm

Problem
Fitness function: @MultiObjective
Number of variables: 5

Constraints:
Linear inequalities: A: b:
Linear equalities: Aeq: beq:
Bounds: Lower: [0,0,0,12.33,100.1667] Upper: [1,1,1,21.33,250.1667]

Run solver and view results
☐ Use random states from previous run

Current iteration: 762

```
Error running optimization.
Output argument "F" (and maybe others) not assigned during call to "C:\Users\Admin\Documents\MATLAB\MultiObjective.m>MultiObjective".
-----------------------
Optimization running.
Changes pending.
Changes applied.
Changes pending.
Changes applied.
Changes pending.
Changes applied.
Changes pending.
Changes applied.
Optimization terminated: average change in the spread of Pareto solutions less than options.TolFun.
```

Pareto front - function values and decision variables

Your solution is too large to be displayed in this table.
Export results to workspace to see your final point.

⊟ Multiobjective problem settings
Distance measure function: ● Use default: @distancecrowding
○ Specify:
Pareto front population fraction: ● Use default: 0.35
○ Specify:

⊟ Hybrid function
Hybrid function: None

⊟ Stopping criteria
Generations: ● Use default: 100*numberOfVariables
○ Specify: 150
Time limit: ● Use default: Inf
Fitness limit:
Stall generations:
Stall time limit:
Function tolerance:
Constraint tolerance:

⊟ Plot functions
Plot interval: 1
☐ Distance
☐ Selection
☑ Average Pareto distance
☐ Custom function:

⊟ Output function
☐ Custom function:

individual. This random number is taken from a Gaussian distribution centered on zero. The standard deviation of this distribution can be controlled with two parameters. The **Scale** parameter determines the standard deviation at the first generation. The **Shrink** parameter controls how standard deviation shrinks as generations go by. If the **Shrink** parameter is 0, the standard deviation is constant. If the **Shrink** parameter is 1, the standard deviation shrinks to 0 linearly as the last generation is reached.

- `Uniform` is a two-step process. First, the algorithm selects a fraction of the vector entries of an individual for mutation, where each entry has the same probability as the mutation rate of being mutated. In the second step, the algorithm replaces each selected entry by a random number selected uniformly from the range for that entry.
- `Adaptive feasible` randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along each direction so that linear constraints and bounds are satisfied.
- `Custom` enables you to write your own mutation function that satisfies any constraints specified. Enter a function handle of the form `@MutateFcn`, where `MutateFcn.m` is a function file with syntax described here.

Crossover

Migration

If you set **Direction** to `Forward`, migration takes place toward the last subpopulation. That is the *n*th subpopulation migrates into the (*n*+1)th subpopulation.

If you set **Direction** to `Both`, the *n*th subpopulation migrates into both the (*n*−1)th and the (*n*+1)th subpopulation.

Figure 3.8: Screenshot of the MATLAB GA Solver

In order to use the GA solver, the user must construct an initial population of chromosomes, as well as determine the crossover and mutation rates to be used. MATLAB’s GA solver also supports adequate flexibility in that the user can select various GA types and set the tolerance and stopping criteria as necessarily needed. The decision to use this platform was made based on what was available and what was known to the author. That being said, other platforms should be explored for better efficiency and functionality.

CHAPTER 4

ILLUSTRATION OF IMPLEMENTATION

This chapter is focused on providing an academic example of how the proposed framework can be implemented. Due to the proprietary nature of cost data, this example is intended to be a simulation for academic purposes only. This chapter will first offer a brief literature review specifically related to the aerospace industry and the use of aluminum and CFRP to impart context to the implementation. The literature review will be followed by an exemplified framework aimed at illustrating the implementation and providing insight for future work.

4.1 Background and Literature Review

4.1.1 Motivation for Aerospace

Why now? Composites have been around for decades and yet they are just now beginning to be used in extended applications? The short answer is yes. Due to recent developments in technology and manufacturing processes, composites have emerged as being a cost effective solution for high valued applications [38]. For example, the commercial sector of the aerospace industry has seen a movement to transition from a predominant aluminum airframe to a more dominant composite airframe. This decision is mostly driven by the weight reduction benefit that results in a lower carbon footprint and lower fuel costs for customers. That being said, composites have also widely been considered non-recyclable, so their growing use in commercial applications leaves unanswered questions for the end-of-life strategy. Pimenta and Pinho [39] suggest that "downcycling", or introducing recycled composites to lower valued applications, may be the answer to close the loop. Though this may be the way to mitigate a lingering problem, it still calls for strategy to be implemented. In fact, there are 6000-8000 commercial aircraft expecting to reach end-of-life in the USA and Europe by year 2030 with each plane containing 20 tons of CFRP (Carbon Fiber-Reinforced Plastics) [40]. 20 tons of a non-recyclable material has to leave one to question the substitution decision to airframes with even more CFRP material. With these unanswered questions, commercial aircraft manufactures are still leading the way with the Boeing 787 having 50% of its weight in CFRP seen in Figure 4.1 and a similar result expected in the new Airbus A350 [41, 42].

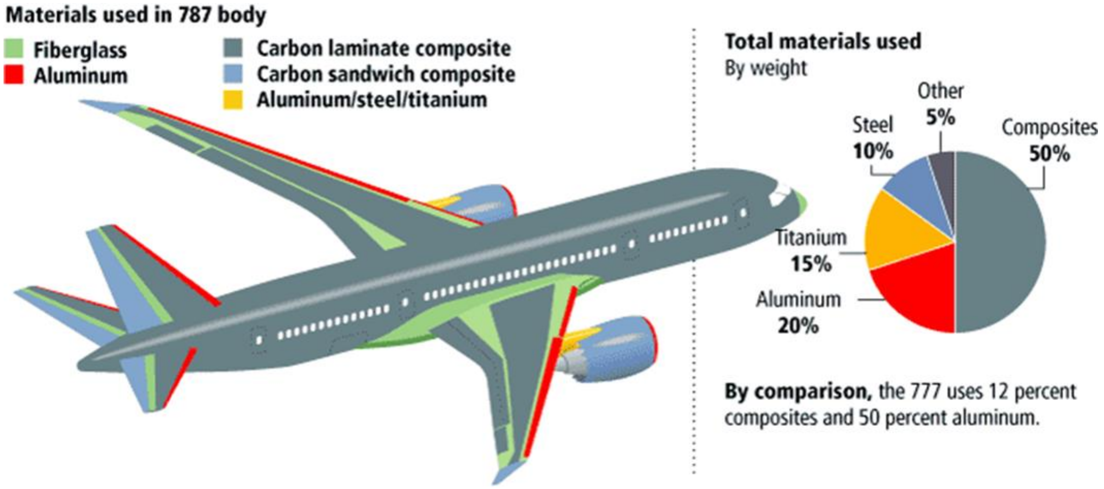


Figure 4.1: Materials used in the 787 body [50]

Therefore, the intention is to apply the proposed framework to this specific case in order to evaluate one of the more controversial material selection design decisions. Due to the lack of and proprietary nature of the data surrounding this case, this application of the framework is strictly for academic purposes and is intended for an illustration of using the proposed framework.

4.1.2 Previous Work

In regards to the use of aluminum and composites in aircraft design and associated optimization, there has been a fairly scarce amount of previous work. Most of the previous work is focused on making comparisons of aluminum and composites, looking at optimization of aircraft structures, and/or a limited scope of costing comparisons between the two. That being said, this section will look at these previous works in order to extrapolate data in the implementation of the proposed framework as well as track the progression of the topic throughout history.

As probably guessed, the onset of composites came out of their use in military and space related operations. In fact, in 1981 a NASA report by Davis and Sakata [43] looked a design considerations for utilizing a composite fuselage in a commercial aircraft. The report addresses structural considerations including things like loading, strain levels, buckling, and damage tolerances as well as manufacturing considerations that include things like material cost, fabrication cost and manufacturability. The report then suggests that there are technical issues and design problems that are associated with using composites that need to be resolved before even considering in future design. Specific areas that are discussed are a need for proven damage tolerance and crashworthiness and a thorough understanding of the principal design drivers. Notice that the end-of-life strategy wasn't even discussed. This is probably in direct correlation with the time period and the design priorities of NASA, but it is still worth noting that the end-of-life isn't even addressed.

Then in textbooks nearly 7 years following the NASA report, composites show up as being a contender in aircraft structural design. Niu [44] states the weight reduction to be the main driver for incorporating composites into designs. Once again, no comment is made on an end-of-life strategy. It is a perfect example of the “iceberg syndrome”. The idea of designing with only the present and initial implications in mind, while being blind to potential problems in the future.

In 2002, Elliott and Kok [45] looked at optimizing the design of fuselage structures. The study aimed at automating the fuselage design process in order to obtain the cheapest and best solution for implementation. In their conclusion, they stated that the use of GLARE (Glass Laminate Aluminum Reinforced Epoxy) panels realized a 20% weight reduction in the overall structure.

Then in 2007, Tooren and Krakers [46] developed a framework for improving the design of fuselage structures, but used aluminum as their specified airframe material. The aim of the research was to use optimization as a means to minimize weight in a fuselage structure while also remaining structurally sound. Although the optimization of design is shown using a GA, there is lack of the consideration of cost and alternate materials.

Kaufmann [47] developed a cost/weight optimization model for aircraft structures. The model focuses on direct operating cost and the weight of the aircraft. It does not provide total life-cycle consideration, nor an end-of-life strategy for the use of composites. However, it outlines a path that can be built upon in future work.

Lambert [48] develops a life-cycle cost model for composite aircraft, but also lacks the total life consideration. The data utilized in the model was provided by the Advanced Composite Cargo Aircraft (ACCA) program and a leading aircraft manufacturer, yet the cost data provided included: manufacturing, design, design support, testing, tooling, logistics, quality assurance, and labor. It can be seen that this is clearly not a consideration of the total life-cycle.

Kennedy and Martinis [49] use an optimization model to make a comparison between metallic and composite wing structures. It is shown that the composite wing designs are 34% to 40% lighter than their metallic equivalent. This results in a fuel savings of 5-8% and take-off weight savings of 6-11%. However, the total life-cycle is still not considered in this study.

Summarizing the review of previous work, there is a need for a total life-cycle approach to examining the material selection decision in aircraft structures. In addition, there is need for an integrated approach of using life-cycle cost data and an optimization framework in order to design and evaluate the optimal structural solution.

4.2 Exemplified Framework

Due to the proprietary nature of costing data, this illustration is completed with a generic aerospace component with generic materials that contain data for simulation purposes only. For this illustration, it will be assumed that the first three steps of the framework have 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.

4.2.1 Identify Candidate Materials

From here, the candidate materials must be identified to utilize the life-cycle cost model and to implement the optimization framework. That being said, the three generic materials will be described by the names Material A, B, and C. Table 4.1 shows the three generic materials and their respective considered material properties.

Table 4.1: List of Generic Candidate Materials

Material Property	Material A	Material B	Material 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
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

4.2.2 Life-Cycle Cost

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 in Table 4.2. This table shows the major cost elements that feed into the overall life-cycle cost.

Table 4.2: Life Cycle Cost Elements for Candidate Materials

Cost Element	Material A	Material B	Material 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

Now, that the life-cycle cost elements are determined for the various materials, the percentage breakdown of material going into each of the various streams must be determined. However, this will be optimized by the algorithm. A single set point can be seen in Table 4.3.

Table 4.3: List of EOL Material Steam Percentages for Generic Candidate Materials

Breakdown	Material A	Material B	Material C
% Recovered	0	95	100
% Recycled	0	45	34
% Remanufactured	0	20	33
% Reused	0	30	33
% Wasted	100	5	0

That being said, the percentage of material recycled, remanufactured, and reused can be plotted in order to compare the impact of the different possible allocation combinations. This can be seen in Figures 4.2-4.5.

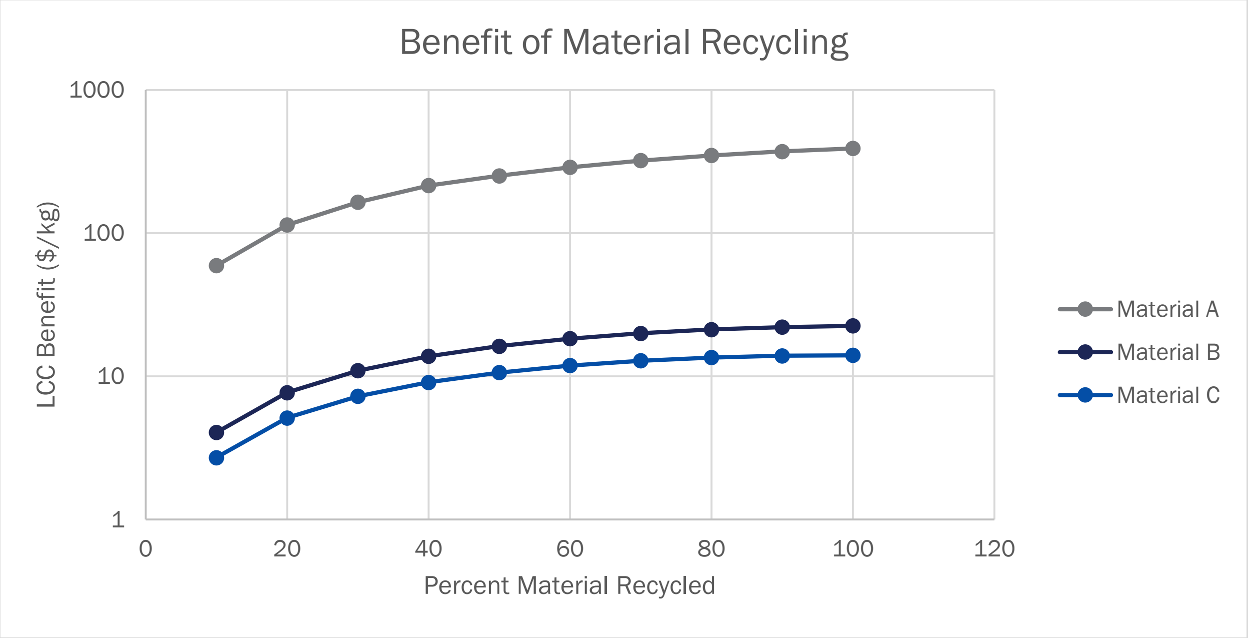


Figure 4.2: Benefit of larger recycling allocation

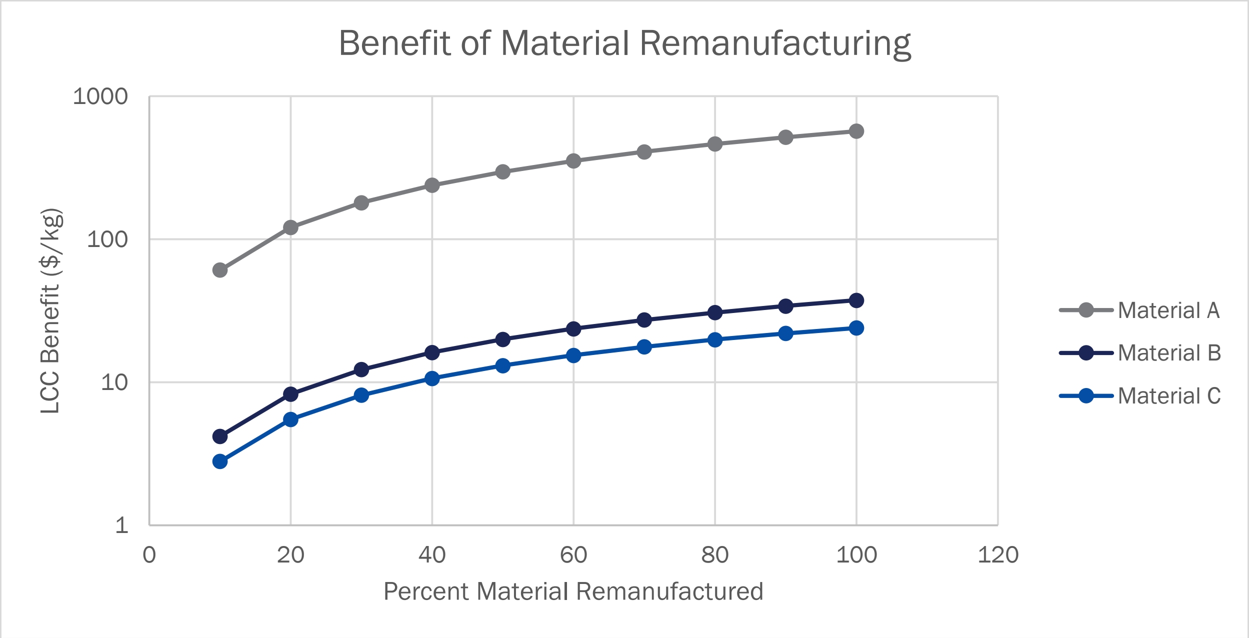


Figure 4.3: Benefit of larger remanufacturing allocation

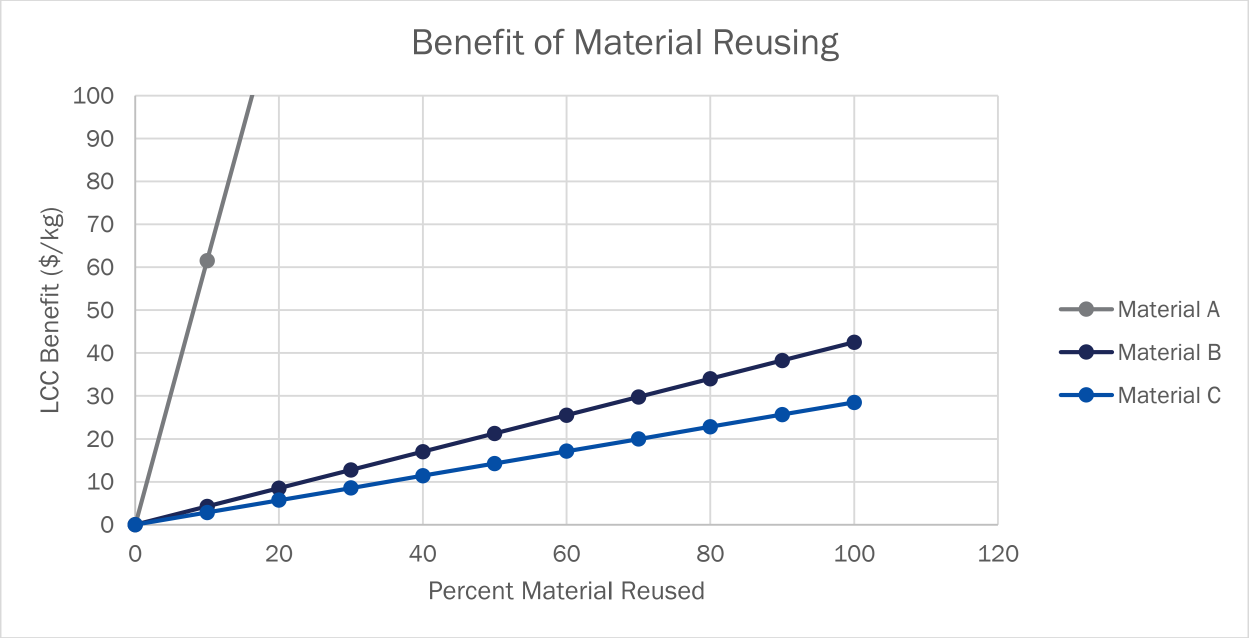


Figure 4.4: Benefit of larger reusing allocation

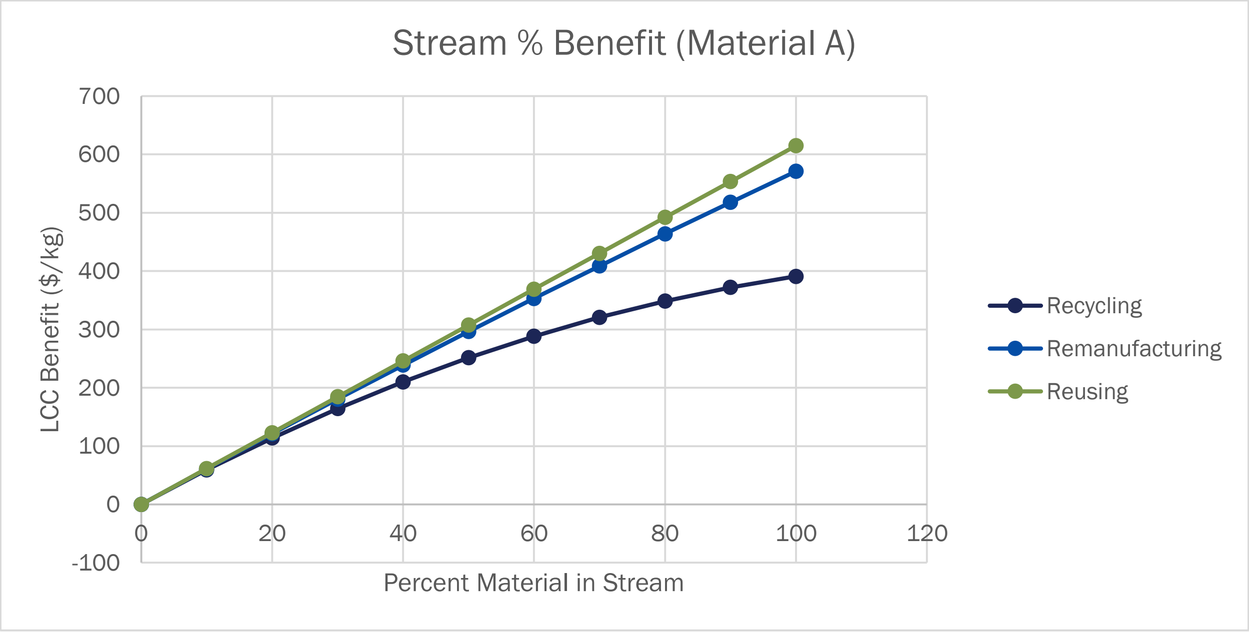


Figure 4.5: Material stream allocation benefit summary

From these plots, it is important to see the benefit of optimization of not only the material, but also the allocation of material to post-use streams. With the stream allocation information, the life-cycle cost of the manufacturer and customer can be determined by the following calculations. This is all done simultaneously within the operation of the algorithm. However, for the purposes of this illustration the calculations are shown for the two generation case below.

$Material\ A$:

$$C_{MFG} = 2\left[\left(\frac{1}{2}+1\right)(22+18)+(0)(0.5)+(0)(0.4)+28\right] = \$176/kg$$

$$C_{CUST} = 2\left(\left(\frac{1}{2}+1\right)176+37+42\right) = \$686/kg$$

$$TLCC = 176+428 = \$862/kg$$

$Material\ B$:

$$C_{MFG} = 2\left[\left(\frac{1}{2} + 0.05\right)(3 + 3) + (.95)(0.5) + (.65)(1) + 14\right] = \$36.9/kg$$

$$C_{CUST} = 2\left(\left(\frac{1}{2} + 0.6\right)36.9 + 37 + 34\right) = \$223.18/kg$$

$$TLCC = 37.45 + 230 = \$260.8/kg$$

$Material\ C$:

$$C_{MFG} = 2\left[\left(\frac{1}{2} + 0\right)(2.1 + 2) + (1)(0.5) + (.67)(1) + 9\right] = \$25.9/kg$$

$$C_{CUST} = 2\left(\left(\frac{1}{2} + 0.7\right)25.9 + 37 + 31\right) = \$198.16/kg$$

$$TLCC = 27.20 + 205.6 = \$224.06/kg$$

Seen in Table 4.4, there is summary of the calculations above with each of the three cases: two generations, five generations, and ten generations.

Table 4.4: Case Summary of LCC of Candidate Materials

Cases	**Material A**	**Material B**	**Material C**
Case 1: Two Generations			
Manufacturer ($/kg)	176.00	36.90	25.90
Customer ($/kg)	686.00	223.18	198.16
Total ($/kg)	862.00	260.08	224.06
Case 2: Five Generations			
Manufacturer ($/kg)	380.00	75.88	47.96
Customer ($/kg)	1307.00	476.40	426.32
Total ($/kg)	1687.00	552.28	474.28
Case 3: Ten Generations			
Manufacturer ($/kg)	720.00	145.75	91.82
Customer ($/kg)	2374.00	914.05	826.91
Total ($/kg)	3094.00	1059.80	918.72

With the life-cycle cost information calculated, the optimization model can now be formulated as it is in the following section.

4.2.3 Optimization Formulation

Shown in this section is the formulated optimization problem for the illustration. For the geometry of the component, a simple cylinder shell was assumed that has 8 “I” beams for support running across the length of the cylinder. In addition, in this optimization formulation, it is assumed that each objective function is equally weighted to the value of the overall fitness function.

Variables

E	Young’s Modulus
ρ	Density

σ_y	Yield Strength
UTS	Ultimate Tensile Strength
T	Shear Strength
HB	Hardness
EI	Environmental Index
SI	Societal Index
r	Primary Radius
t	Cylinder Thickness
L	Component Length
b	Beam Characterization Factor
C_{MFG}	Life-Cycle Cost to Manufacturer
C_{CUST}	Life-Cycle Cost to Customer
$TLCC$	Total Life-Cycle Cost

<u>Objectives:</u>

(1) Maximize Stiffness Pressure Vessel: E/ρ

(2) Maximize Failure Strength Pressure Vessel: σ_y/ρ

(3) Minimize Manufacturer Life-Cycle Cost

$C_{MFG}\rho(2\pi rtL + 8b^2)$

(4) Minimize Total Life-Cycle Cost

$TLCC\rho(2\pi rtL + 8b^2)$

<u>Subject to:</u>

Customer/Manufacturer Relationship

$$-K(C_{MFG_{Current}} - C_{MFG_{Baseline}}) \geq C_{CUST_{Current}} - C_{CUST_{Baseline}}$$

Environmental Performance Relationship

$$EI_{New}V_{New} \leq EI_{Baseline}V_{Baseline}$$

Societal Performance Relationship

$$SI_{New}V_{New} \leq SI_{Baseline}V_{Baseline}$$

Functional Performance Limit

$$Buckling(Euler):\ 5kN \leq \frac{29\pi^2 E(\frac{b}{100})^4}{L^2}$$

Geometric Constraints

$$3.5 < r < 8$$

$$0.2 < t < 0.75$$

$$10 < L < 25$$

$$1 < b < 5$$

4.2.4 Results and Discussion

The optimization formulation was the coded in MATLAB to utilize its multi-objective genetic algorithm toolbox. The raw code can be seen in Appendix A. 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. The final populations of each of the three cases can be seen in Appendix B, while a summary of the results can be seen in Table 4.5.

Table 4.5: Summary of Results for each Case Ran

Cases	Material	Radius(m)	Thickness (cm)	Length (m)	Support Beam
Case 1: Two Generations	Material B	4.55	0.45	11.13	2.50
Case 2: Five Generations	Material B	4.50	0.46	11.00	2.50
Case 3: Ten Generations	Material B	3.50	0.20	10.01	3.19

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

To understand what this means, the genetic algorithm and the nature of multi-objective optimization itself must be understood. The 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 that will be discussed in the next section.

CHAPTER 5

CONCLUSIONS

5.1 Concluding Remarks

5.1.1 Assumptions

For this framework, there are assumptions that were made that affect the accuracy and applicability of the model that must be clearly stated. The following list is comprised of the major assumptions that have been determined to not be common knowledge and are needed to be explicitly stated:

1. The material properties are assumed to be constant moving from generation to generation. This is obviously known not to be the case with recycled, reused, and remanufactured material. A way to address dynamic material properties must be considered in the future of this work.
2. The life-cycle cost of a component is assumed to be a linear function of amount of material. Although, a valid starting point, incorporation of machine learning techniques and/or more complex mathematical models must be considered for the future of this work.
3. In terms of post-use material streams, it is inherently assumed in the methodology that the recyclability stream incurs a higher cost than the remanufacturing stream which incurs a higher cost than the reuse stream. However, the life-cycle cost model equations do have the ability to adapt to this mathematically.

Although assumptions have been made, they are determined to be reasonable in order to prove the concept of such a framework. That being said, the overall view and contribution of the work will be discussed in the following section.

5.1.2 Overview of Work

In Chapter 1, the motivation behind the thesis was discussed. It was determined that there is a need for a component level sustainable material selection method that is objectively implemented by the means of life-cycle costing. It was shown that this method should be a method in which the total life-cycle is in mind to be able to realize the 6R benefit. It should also be integrated into the conceptual design stage in order to provide designers with adequate information to make informed and sustainable decisions before they become cost prohibitive. In addition, it should be done at the component level in order to individually evaluate singular components within a large assembly. Following the motivation, the proposal of the thesis was given and justified. It was proposed to be a framework for sustainable material selection for multi-generational components.

Chapter 2 provides a literature review that goes into previous work regarding the relevant topics that are presented in this thesis. The areas that are covered are: 6R concept and the circular economy, life-cycle costing, material selection in design, and multi-objective optimization. The literature review provides a basis for the methodology that lies behind the framework.

In Chapter 3, the framework is reviewed in detail. First, the life-cycle cost model is presented and discussed for the use with multi-generational components. Second, the accompanied optimization framework is broken down to its components and thoroughly reviewed. Finally, the procedure of the framework, as well as the platform used for implementation is discussed.

Chapter 4 is meant to illustrate the implementation of the framework that was described in Chapter 3. To illustrate the framework, the fuselage structure of an aircraft was the chosen component. Although it is an academic example that is based off of generated data, it lays the foundation for future developments.

With that being said, the contributions of this framework should be clarified. The novelty comes from the utilization of the life-cycle cost for the complete life-cycle as the means to evaluate the sustainability of a component. 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 data in the evaluation of relevant case-studies, such as the fuselage of a commercial aircraft. In addition, it lays the groundwork for the development of a design tool that can be integrated into traditional design processes.

5.2 Future Work

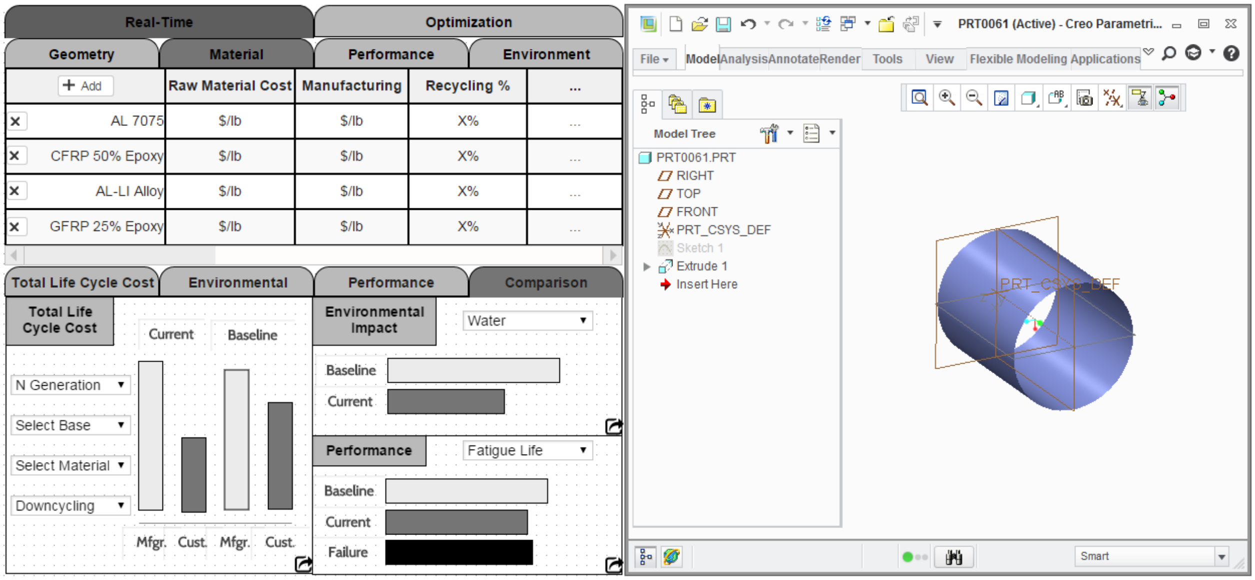
5.2.1 Application to Relevant Case Studies

Future work should be focused on applying the framework to relevant case studies that provide a unique perspective on this type of product design. These applications should include the use of industry provided data in order to comprehensively implement the full framework. Chapter 4 lays out the illustration of the implementation of the framework.

This provides the ability to easily interject the illustration with industry provided data to make informed conclusions about material selection decisions. The framework is also intended to be versatile in application and should be applied to a various number of industries in order to understand the impact in each. These applications would not only be useful in further validating the suggested framework, but they would also be useful in determining the business case by quantifying the sustainable value creation that is a direct result of its implementation.

5.2.2 The Overall Vision

The overall vision of this framework includes it one day being integrated into existing CAD packages where product designers have the ability to design sustainably in “real-time”. The idea presented for getting to this point is to leverage the same machine learning technology that was used to bring the world facial recognition and to use it for product design. This would involve using a Neural Network, or something similar, and using it to identify patterns in the geometrical complexity of a population of designed components and their respective total life-cycle costs in order to be able to predict the impact of design changes on the life-cycle costs of future components. In other words, the vision would look like the mock-up shown in Figure 5.1, except more robust in its final implementation.



	Raw Material Cost	Manufacturing	Recycling %	...
✕ AL 7075	$/lb	$/lb	X%	...
✕ CFRP 50% Epoxy	$/lb	$/lb	X%	...
✕ AL-LI Alloy	$/lb	$/lb	X%	...
✕ GFRP 25% Epoxy	$/lb	$/lb	X%	...

Figure 5.1: Mock-Up of the framework being integrated into a CAD package

This would mean that as designers changed dimensions or geometry, the trade-off in total life-cycle cost would immediately be able to be seen. The result of an implementation of this scale and of this caliber would mean an unprecedented ability for designers and manufacturers to know the impact of their decisions prior to even making them. This would give the manufacturing world the ultimate tool for designing sustainable products, as well as the ultimate tool for manufacturers to realize significant cost savings.

APPENDICES

APPENDIX A

Matlab Code

Objective Function:

```
function [F] = MultiObj2(M)
%MultiObjective Material Selection

 load('materials.mat')

 %Generations
 G=2;

 %Selection of Material Properties to use to evaluate objective
functions
 if M(2)>M(1) andand M(2)>M(3)
     M(2)=2;
     %Total Recovered
     Rec=M(8)+M(9)+M(10);
     %Remanufacturing, Recycling, Reusing
     RRR=M(8)*3+(M(8)+M(9))*1-3;
     %Mfg LCC
     MLCC=G*((1/G+(1-Rec))*(6)+Rec*0.5+(Rec)*RRR+14);
     %Cust LCC
     CLCC=G*((1/G+0.6)*(2*(MLCC/G))+37+34);
     %Total LCC
     TLCC=MLCC+CLCC;
     %Obj 1: Stiffness Pressure Vessel
     F(1)=1/(materialsmat(1,M(2))/materialsmat(2,M(2)));
     %Obj 2: Failure Strength Pressure Vessel
     F(2)=1/(materialsmat(3,M(2))/materialsmat(2,M(2)));
     %Obj 3: MLCC
     F(3)=materialsmat(2,M(2))*(MLCC)*((2*pi*M(4)*M(5)+8*M(7)^2)*M(6));
     %Obj 4: TLCC
     F(4)=materialsmat(2,M(2))*(TLCC)*((2*pi*M(4)*M(5)+8*M(7)^2)*M(6));

 elseif M(1)>M(2) andand M(1)>M(3)

     M(1)=1;
     %Total Recovered
     Rec=M(8)+M(9)+M(10);
     Rec=0;
     M(10)=0;
     %Remanufacturing, Recycling, Reusing
     RRR=M(8)*18+(M(8)+M(9))*4.4-22;
     %Mfg LCC
     MLCC=G*((1/G+(1-Rec))*(40)+Rec*0.5+(Rec)*RRR+28);
     %Cust LCC
     CLCC=G*((1/G+1)*(2*(MLCC/G))+37+42);
```

```
     %Total LCC
     TLCC=MLCC+CLCC;
     %Obj 1: Stiffness Pressure Vessel
     F(1)=1/(materialsmat(1,M(1))/materialsmat(2,M(1)));
     %Obj 2: Failure Strength Pressure Vessel
     F(2)=1/(materialsmat(3,M(1))/materialsmat(2,M(1)));
     %Obj 3: MLCC
     F(3)=materialsmat(2,M(1))*(MLCC)*((2*pi*M(4)*M(5)+8*M(7)^2)*M(6));
     %Obj 4: TLCC
     F(4)=materialsmat(2,M(1))*(TLCC)*((2*pi*M(4)*M(5)+8*M(7)^2)*M(6));

 else

     M(3)=3;
     %Total Recovered
     Rec=M(8)+M(9)+M(10);
     %Remanufacturing, Recycling, Reusing
     RRR=M(8)*2+(M(8)+M(9))*0.9-2.1;
     %Mfg LCC
     MLCC=G*((1/G+(1-Rec))*(4.1)+Rec*0.5+(Rec)*RRR+9);
     %Cust LCC
     CLCC=G*((1/G+0.7)*(2*(MLCC/G))+37+31);
     %Total LCC
     TLCC=MLCC+CLCC;
     %Obj 1: Stiffness Pressure Vessel
     F(1)=1/(materialsmat(1,M(3))/materialsmat(2,M(3)));
     %Obj 2: Failure Strength Pressure Vessel
     F(2)=1/(materialsmat(3,M(3))/materialsmat(2,M(3)));
     %Obj 3: MLCC
     F(3)=materialsmat(2,M(3))*(MLCC)*((2*pi*M(4)*M(5)+8*M(7)^2)*M(6));
     %Obj 4: TLCC
     F(4)=materialsmat(2,M(3))*(TLCC)*((2*pi*M(4)*M(5)+8*M(7)^2)*M(6));
 end



end
```

Constraint Function:

```
function [ c, ceq] = constraints(x)


load('materials.mat')
%Generations
G=2;
Rec=x(8)+x(9)+x(10);

if x(1)>x(2) andand x(1)>x(3)
    a=1;
    RRR=x(8)*18+(x(8)+x(9))*4.4-22;
    Rec=0;
    pl=x(10);
    %Mfg LCC
     MLCC=G*((1/G+(1-Rec))*(40)+Rec*0.5+(Rec-0)*RRR+28);
     %Cust LCC
     CLCC=G*((1/G+1)*(2*(MLCC/G))+37+42);
elseif x(2)>x(1) andand x(2)>x(3)
    a=2;
    RRR=x(8)*3+(x(8)+x(9))*1-3;
     %Mfg LCC
     MLCC=G*((1/G+(1-Rec))*(6)+Rec*0.5+(Rec)*RRR+14);
     %Cust LCC
     CLCC=G*((1/G+0.6)*(2*(MLCC/G))+37+34);
else
    a=3;
     RRR=x(8)*2+(x(8)+x(9))*0.9-2.1;
     %Mfg LCC
     MLCC=G*((1/G+(1-Rec))*(4.1)+Rec*0.5+(Rec)*RRR+9);
     %Cust LCC
     CLCC=G*((1/G+0.7)*(2*(MLCC/G))+37+31);
end


c(1)=((((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,a)*CLCC)-
(((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,2)*(164.5*G))+((((2*pi
*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,a)*MLCC)-
(((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,2)*(50*G))));

c(2)=-((14.67*pi^2*materialsmat(1,a)*1e9*(x(7)/100)^4)/(x(6)^2))+5000;

c(3)=(((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,a)*materialsmat(7
,a))-(((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,2)*0.63);

c(4)=(((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,a)*materialsmat(8
,a))-(((2*pi*x(4)*x(5)+8*x(7)^2)*x(6))*materialsmat(2,2)*0.665);

ceq=0;


end
```

APPENDIX B

Final Population Results

Two Generations Case

Material A	Material B	Material C	Radius (m)	Thickness (cm)	Length (m)	Support Beam	% Recycled	% Remanufactured	% Reused
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.634	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.633	0.167
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0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.634	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.634	0.167
0.283	0.399	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.634	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.451	11.1	2.50	0.201	0.633	0.167

0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.634	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167
0.283	0.400	0.319	4.55	0.452	11.1	2.50	0.201	0.633	0.167

Five Generations Case

Material A	Material B	Material C	Radius (m)	Thickness (cm)	Length (m)	Support Beam	% Recycled	% Remanufactured	% Reused
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201

0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.200
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.200
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201

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0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
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0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201

0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201

Ten Generations Case

Material A	Material B	Material C	Radius (m)	Thickness (cm)	Length (m)	Support Beam	% Recycled	% Remanufactured	% Reused
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.422	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067

0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.422	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067

0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067

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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
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0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.223	0.421	0.357	3.50	0.202	10.0	3.19	0.518	0.416	0.067
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201
0.231	0.736	0.034	4.50	0.455	11.0	2.50	0.735	0.065	0.201

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