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Sustainable Design of a Reusable Water Bottle: A Systems Thinking Approach

Hossein Basereh Taramsari[a]*, Dr. Steven Hoffenson[a]

[a]*Stevens Institute of Technology, School of Systems and Enterprises, Hoboken, NJ 07030, USA*

Abstract

Despite the efforts to increase the pace of sustainable design adaptation in industries, several systemic barriers currently hinder this shift. The design for sustainability methods have been utilized in product design and development phases in many industries. However, they do not have a holistic approach that can capture these systemic drivers and barriers while considering all three pillars of sustainability: environmental, social, and economic. This research proposes a systems thinking approach toward sustainable design that can collectively consider different aspects of the production system in an attempt to resolve the multi-dimensional challenges within the design for sustainability. A reusable water bottle is selected as the case study to illustrate the applications and limitations of this approach. In addition, this case study also helped to define the boundaries and stakeholders involved in the system and reduce the abstractions. The results from this analysis are demonstrated as a causal loop diagram that could be implemented in a system dynamics model to quantitatively identify the systematic forces and leverage points driving sustainable design in product development. The comprehensive understanding provided by this analysis revealed many improvement possibilities, trade-offs, and feedback loops within the system that can assist in realizing sustainable product design proliferation and associated positive sustainability outcomes.

Keywords: Design for sustainability; Systems thinking; Complexity; Product development; Reusable water bottle

1. Introduction

Achieving sustainability has become one of the major global concerns in recent years, and its implementation in product development and design has gained high importance due to its significant impact. The Brundtland report famously defined sustainability as "development that meets the need of the present without compromising the ability of future generations to meet their own needs"[1]. Sustainability research has received high interest in recent years since

* Corresponding author. Tel.: +1-201-216-5000
E-mail address: hbasereh@stevens.edu

its importance has been emphasized by international agencies such as United Nations (UN). The UN 2016 report identified 17 sustainable development goals (SDGs) that call for sustainable improvements in environmental, social, and economic sustainability[2]. Since then, the company's and consumer's perspective toward sustainability has changed, and many companies are trying to utilize sustainable methods within their organization. These 17 SDGs cover three sustainability categories: environmental, social, and economical, following the "triple bottom line" concept where sustainability is considered in terms of people, planet, and profit[3]. In this strategy, sustainable design can provide quality for the consumer, reduce environmental emissions, and create more profit for companies. Implementing the triple bottom line within design for sustainability (DfS) has been a complex challenge due to the interconnected dependencies of different stakeholders within the system of the product. These stakeholders each seek different objectives that have conflicts and contribute to increasing the complexity of sustainable design. It is challenging for design engineers to utilize current sustainable design tools and methods because of the wide range of available methods, and most of them try to address one aspect of sustainability. Powerful tools and methods have been designed to assist companies, specifically designers, in considering different sustainability aspects, but still, most are not implemented or utilized. There are several reasons why these tools and methods are not implemented, and one of the main reasons is the lack of a holistic approach toward sustainability within these frameworks.

This research aims to address the complexity of this holistic approach toward sustainability by applying systems thinking methods. The proposed method can provide a deeper understanding of the system's current state while creating a model that can be extended quantitatively to describe the system's dynamics. In a systems thinking approach toward sustainable product design, the links between the stakeholders can be identified and analyzed to create a model that can accurately demonstrate the system. This research aims to reveal the dependencies and connections between different stakeholders surrounding a reusable water bottle by applying systems thinking methods. The expectation is that the final model can result in a system dynamics model that can assist stakeholders in implementing sustainability tools within product development and design in a holistic manner. It can also be used to identify leverage points to improve system outcomes. This research focuses on a reusable water bottle's cradle-to-cradle life cycle impact by considering multiple stakeholders and their decisions. The research question addressed in this paper is: What dependencies and relationships exist among the stakeholders of the reusable water bottle and the different life cycle phases of the product? Moreover, where are the key leverage points in this system? The following sections include background about sustainable design and systems thinking, methodology describing the systemic approach, and the resulting model.

2. Background

An overview of sustainable design and systems thinking approaches, practices, and previous research in this field is described in the following sections.

2.1. Sustainable Design

Production and consumption practices in global societies are some of the key contributors to the sustainability problems we face today. Companies need to transform and adopt new design, development, and manufacturing modes to achieve global sustainability goals[4]. Several companies have made some small steps in recent years toward loosening their resistance to sustainable design due to the rise of sustainability activism and the shift in the market towards sustainable goods and services[5]. A growing list of methods and tools have emerged over the past few decades that can use analytical techniques to reveal the environmental impacts of the products to the companies[6]. Life cycle assessment (LCA) is an example of the analytical tools developed to measure sustainability based on a product's environmental impacts through its life cycle[7]. A product's life cycle is generally composed of raw material acquisition, manufacturing, distribution, usage, and disposal, but may differ depending on the nature of the product in question. LCA was initially utilized to analyze the environmental impacts of beverage containers, and it began to integrate environmental concerns into the critical product development phases: concept design, part design, process design, and decision-making[8]. One of the significant downfalls of LCA is its high dependence on data quality and the need to quantify all factors, even those with natively qualitative attributes[8]. Designers have not widely used these tools because some are product specific or do not address the sustainability problem holistically.

Researchers have emphasized the importance of systemic[9] and strategic[10] adaptation of sustainability in product development instead of separate modifications for each aspect of sustainability in design[11]. This systemic transition toward sustainability requires the identification of interdependencies among different dimensions and stakeholders and deepening the understanding of their interactions[12]. Such understanding would reveal the leverage points that can assist the system in achieving its higher-level objectives locally or globally.

2.2. Systems Thinking

System thinking has been used to study the dynamic behavior of a complex system by identifying and understanding the relations and patterns of the system. Kim[13] has defined systems thinking as "a way of seeing and talking about the reality that helps us better understand and work with systems to influence the quality of our lives." In this framework, a system consists of three core components: elements (parts), interconnections (interaction), and function (goal). The system is viewed as "any group of interacting, interrelated or interdependent parts that form a complex and unified whole that has a specific purpose"[13,14].

Researchers have previously looked at sustainability from the lens of complex system dynamics[12,15,16], where effective leverage points in several system domains and subsystems were investigated using systems thinking techniques. Some robust systems thinking tools have been identified as: system archetypes, behavior over time graphs, causal loop diagrams, systemigrams, stock and flow diagrams, root cause analysis, and interpretive structural modeling[17,22]. Each tool has specific advantages and limitations in analyzing complex problems. Sterman[18] has pointed out that positive and negative feedback loops exist within all elements of the system that influence the system's behavior. These feedback loops are represented using a causal loop diagram (CLD) method that can capture the communicating feedback loops that may be responsible for a particular problem[18]. The first step in generating a system dynamics model is to create a CLD using stock and flow functions[19], but CLD has also been used independently as a systems analysis tool[20]. Richards et al.[21] used a CLD to explore the negative impacts of climate change on agricultural systems, food supply, economic shocks, socio-political instability, starvation, and migration issues.

A CLD consists of elements of the system (variables) connected by arrows, and it demonstrates the causal influences between them. Two general causal loop types exist: positive (reinforcing loop) or negative (balancing loop), which defines the functional architecture of the system[18]. The CLD is an effective tool to identify leverage points where small interventions could significantly impact system behavior[14]. Applying a systems thinking approach toward sustainability provides a comprehensive overview of the system of interest and the interaction between its elements.

3. Methods

The methodology of this research combines different classical and modern approaches to systems thinking in order to tackle the sustainability challenge in product design. The causal loop diagram (CLD) requires a reasonable understanding and knowledge of the elements within the system to provide an accurate model. Nine steps are identified in this framework to generate the CLD and meet the research objective defined. These steps are: (1) defining characteristics, (2) identifying stakeholders, (3) interest map, (4) perspective analysis of system's stakeholders, (5) value-adding processes, (6) analysis of systematic forces, (7) complexity analysis, (8) customers, actors, transformation, world view, owner and environment (CATWOE), and (9) causal loop diagram (CLD). The eight initial steps are selected to generate a clear understanding of the system and its current state, and the final result of the analysis is the CLD generated.

Defining the characteristics of these stakeholders is the first step in this systematic approach. This characterization can be geographical, infrastructural, social, etc. This step helps define a boundary for our system and understand the domain of interest. The system's stakeholders are identified in the second step, where the agents directly or indirectly connected to the system are selected. These agents can make decisions influencing the system's performance or outcomes. Therefore, it is essential to identify all the system's stakeholders inside this systematic approach. Based on the information created in the previous steps, an interest map is developed, which is the third step of this systematic approach. The interest map illustrates the interactions among stakeholders and resources of interest or goals. The fifth step is to identify the value-adding processes that have not been included in the existing system and investigate their causes. Then by listing the shaping forces that impacted the system throughout time, we can explore the possibility of influencing these shaping forces in the sixth step. The analysis of systematic forces reveals a robust understanding of the roots of the problems within the system. The seventh step is the complexity analysis of the system. In this step, simplification methods of modeling the system can be specified by evaluating the complexity of the system's components. This is the first step toward modeling the system, and the assumptions built here are used as the foundation of the research. The CATWOE technique is the eighth step to define and analyze different customers, actors, transformation, world view, owners, and environment of the system.

In the last step of the analysis, the analyzed system defined in the previous steps is used to create the CLD that can provide a holistic understanding of the system's interrelationships. This diagram can be the foundation to create a quantitative dynamic model of the holistic product design system. To reduce the abstraction of the model, a reusable water bottle (RWB) is selected as a case study to illustrate the mechanism of this methodology. This product has meaningful environmental and social impacts, and it is a consumer-based product with a simple mechanism. A systematic approach toward design for the sustainability of the reusable water bottle can provide insights into the proposed framework's application and limitations when applied to consumer products.

4. Results

4.1. Defining Characteristics

The reusable water bottle case study used in this research is assumed to be manufactured, sold, used, and disposed in the United States. The environmental life cycle of the product consists of extracting raw materials, processing raw materials, transporting the materials to the manufacturing site, manufacturing the components, assembling the final product, labeling and packaging the product, transporting the product to the retailer, customers using the product (wastes), and disposing of the product at the end of its useful life. The end of life of products depends on the decisions available for customers, which can either be disposed to landfill or recycled based on the recyclability of the reusable water bottle's materials. The sustainability analyzed within this system concerns environmental, social, and economic sustainability. Environmental sustainability includes humans, ecosystems, and natural resources available, social sustainability is in terms of human health and equity, and economic sustainability consists of the economic growth of the society. This reusable water bottle’s defining characteristics are its specifications: weight, volume, heating efficiency, reliability, durability, portability, washability, geometric values (thickness and diameter), and price. These specifications are the major parameters that can describe the product's quality and evaluate its performance.

4.2. Identifying Stakeholders

A general theme is selected for the stakeholder identification process of this system. These stakeholders will then be divided and categorized into smaller agents. The stakeholders identified for the reusable water bottle are the general public, the environment, the government, and businesses. Each of the stakeholders mentioned has sub-divisions that include agents with different decision-making. For example, the general public consists of personnel hired for processing/manufacturing reusable water bottles and customers/users. Since the general public is a stakeholder in this system and the product has long-lasting environmental and social impacts, the future generation who are not born yet are also members of this stakeholder category.

4.3. Interest Map

The interest map of the system illustrated in Figure 1 shows an overview that captures the system's stakeholders, agents, and goals/objectives. The general public is mainly concerned with maximizing positive social impacts, product quality and minimizing environmental impacts and wastes. The natural and built environments aim to minimize environmental impacts and waste. Businesses seek to maximize the profit and quality of the product and minimize waste. In addition, maximizing positive social impacts, product quality, and economic growth, and minimizing environmental impacts and waste are the government's objectives. According to the interest map, the stakeholders have several common goals, but some cannot be achieved simultaneously, and the trade-offs are the critical factors in this system. For example, maximizing the quality of the reusable water bottle requires extracting materials such as stainless steel, which maximizes the environmental impact.

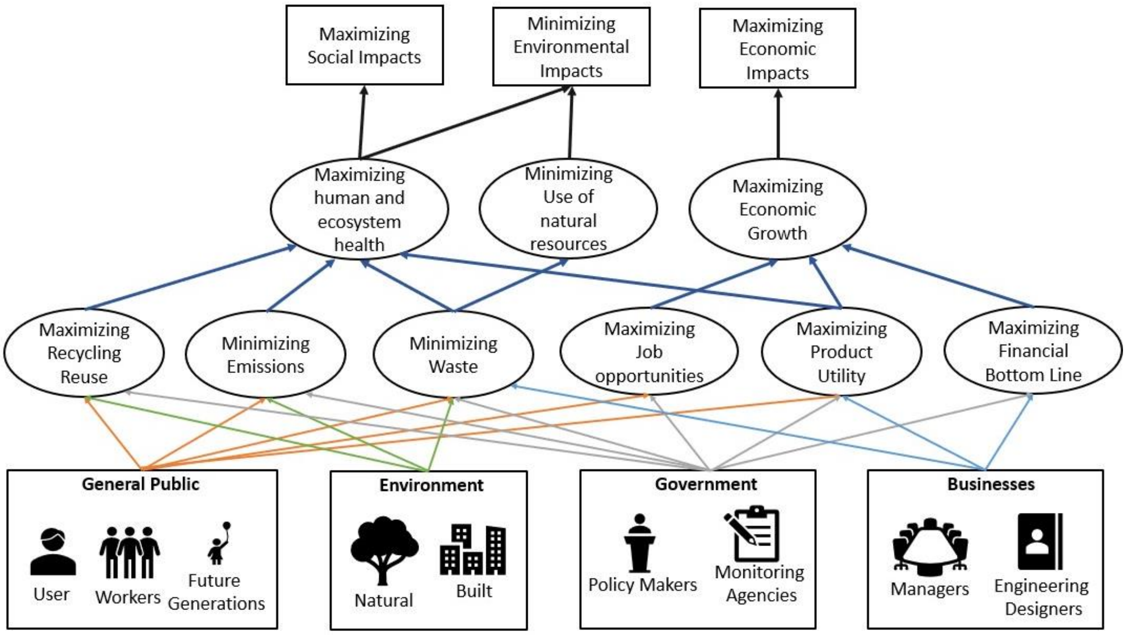

Fig. 1. Interest map of the system's stakeholders

4.4. Perspective Analysis

Considering the holistic sustainability metrics, which are environmental, social, and economic, the system's objectives are mainly similar for stakeholders, but their perspectives can be examined to create a more comprehensive understanding of the system's elements. The reusable water bottle example can be used here to specify many aspects of the stakeholder's perspective. The company's managers want satisfied customers who purchase more reusable water bottles, which leads to maximizing their profits. Therefore, engineering designers need to design a reusable water bottle that meets the requirements of the user and satisfies the government's requirements and regulations. The significant attributes influencing the decision of the customer/user are the product's quality, affordability, and sustainability level. The quality factor depends on many parameters, such as material and manufacturing processes, which impact the product's durability, reliability, portability, and heating efficiency. The policymakers (government) want to create a balance between minimizing the environmental impacts caused by different life phases of the product and maximizing the economic growth of the society while also protecting the general public. The environment does not have an agency that can represent a perspective, but the environmental awareness and concerns of the society reveal themselves in terms of customers' choices and the government's policies and regulations.

4.5. Value-adding Processes

The reusable water bottle's purpose is to work as a container that holds water or other liquids, and to possibly also maintain a desired hot or cold temperature over time. The value-adding processes included within this system are productivity, well-being, health, equity, environmental sustainability, and economic advancements. The production of reusable water bottles increases productivity, and the customers' well-being and health can increase by increasing their hydration level. Equity can increase in the workplace where this product will be manufactured and retailed. Environmental sustainability can increase within the product's design and end-of-life choices, and economic advancements can be achieved by improving the design and expanding the product's market.

4.6. Analysis of Systematic Forces

Three main systematic forces were identified for this system which are environmental, economic, and technological forces that shaped the system's current state. The environmental force is due to limited natural resources available and the long-lasting negative environmental impacts caused during the product's different life stages. These environmental factors significantly affect society's well-being, making it a major systemic force influencing the system. The economic growth required for our modern society to sustain itself asks for increasing production and meeting the demands while also providing sufficient job opportunities for society. The technological forces are the advancements in utilizing sustainable materials and processes within the modern product development and production system that can help create the balance between the environmental and economic forces.

4.7. Complexity Analysis

Complexity science seeks to understand and respond to dynamic and unpredictable problems which are multi-dimensional and have several interrelated elements[22]. In the systems thinking approach toward sustainability, we want to focus on the interactions among variables within this system rather than investigating them separately. There are multi-objective considerations for sustainability, which require a detailed and comprehensive understanding of the interdisciplinary fields involved in this system. In addition, it is always necessary to have a long-time horizon that can benefit all the stakeholders. Figure 2 shows the Cynefin framework[23], which can be utilized as a conceptual framework to assist decision-makers in identifying the system domain. The engineering design section of the product and many aspects of the technical design of sustainability can be considered complicated, requiring sense, analysis, and response. However, considering the cause-and-effect relationships, the sustainability problem defined in this research is in the category of complex problems mainly due to environmental, social, and economic aspects. The social aspects of product usage, such as user behavior or decision-making, are more complex because reusable water bottles have diverse customers, and multiple variables influence their decision-making. Various technological advancements can address the current sustainability challenges, such as recycling materials in the future which makes the problem unpredictable. The interdependencies between the stakeholder's decisions and the product's life cycle stages require systemic analysis and investigation. Overall, while a reusable water bottle itself is a simple product, the problem of designing such a product in the context of the stakeholders and environment is complex and requires probing, sensing, and responding.

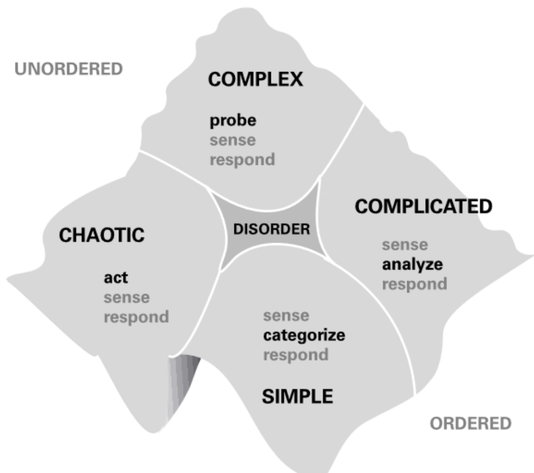

Fig. 2. Cynefin framework[23]

4.8. CATWOE

The reusable water bottle customers are a wide range of people, from students, athletes, drivers, etc. Actors of this system are design engineers, company managers, customers, and policymakers. Transformation happens within the change of direction from the business management perspective, new technological advancements implemented by engineering designers, and customer behaviors. The world view of this product is positive because it is reusable and can potentially replace plastic water bottles that significantly negatively impact the environment through resource consumption and waste streams. Owners of this system are the company who holds the product's intellectual property and the customer who purchased it from the retailer. This product does not have a specific environment and is owned by various customers in different environments.

4.9. Causal Loop Diagram (CLD)

The final result of applying these systems thinking tools is the causal loop diagram shown in Figure 3. In this causal loop diagram, system elements are identified along with their dependencies and interconnections. The positive (+) arrow indicates that the variables change together in the same direction, whereas a negative (-) arrow indicates that they change in opposite directions. This CLD model consists of 33 nodes that demonstrate the decisions of each stakeholder along with the life cycle phases and sustainability goals. The disposable water bottles produced and sold are also included in this system to understand the impacts of reusable water bottles by replacing the disposable ones.

5. Discussion

The system of stakeholder decisions in the sustainable design of the reusable water bottle provided a multi-dimensional perspective to understand the system's elements interactions. The green elements of the CLD representing the sustainable goals demonstrate different dimensions of sustainability. The human and ecosystem health level and the natural resources available are considered environmental sustainability factors. The human and ecosystem health level is also an essential part of social sustainability that encompasses the hydration level of people, jobs created for production, and future generations' health level. In addition, the jobs created for society's production and economic growth are relevant to the economic aspect of sustainability.

There are eleven different specifications of design that are identified as engineering designer's decisions. According to the CLD, the changes in these decisions are highly related to general public variables such as consumer demand, the number of uses before disposal, and customer satisfaction. These variables influence sales and eventually generate profit for the company. The weight, volume, and material quality are three critical parameters identified in the design decisions that directly impact the cost of the reusable water bottle. In the product's use phase, the water and detergent consumption for washing the reusable water bottle is identified as an element directly increasing the emissions to air and water. The product's washability is linked with bottle mouth diameter, and if the washability is high, the customer uses this product more and consequently uses more water and soap to wash it. The benefit, though, is that it increases the product life and therefore the impacts from manufacturing are spread across more functional uses. The durability, reliability, and heating efficiency of the bottle influences the number of uses and, consequently, customer satisfaction, and the thickness of the bottle impacts these elements as well. The thickness is an input for weight and volume; increasing it would increase the cost and decrease the product's portability. The mapping of these decisions shows how finding a balance between these variables can significantly improve the product's sales, profit, and customer experience with the product.

The general public section of the system, shown with orange variables, includes word of mouth and consumer demand, both outputs of societal awareness and concerns about sustainability. Demand, word of mouth, and customer satisfaction are inputs that positively influence the sales of reusable water bottles, an element associated with the business manager stakeholders. One major goal of the general public in this system is to increase people's hydration level, which is a health-related goal with both environmental and social impacts. While purchasing reusable water bottles increases the number of customers, it decreases disposable water bottles produced and sold. This replacement has positive and negative consequences, which should be analyzed. With the replacement of disposable water bottles, there are positive environmental impacts in terms of natural resources available and human and ecosystem health levels. However, the decrease in the production of disposable water bottles may impact the hydration level of people and certain jobs negatively. The increased production of reusable water bottles should compensate to some extent for these negative impacts caused by the consumer shift toward using reusable water bottles.

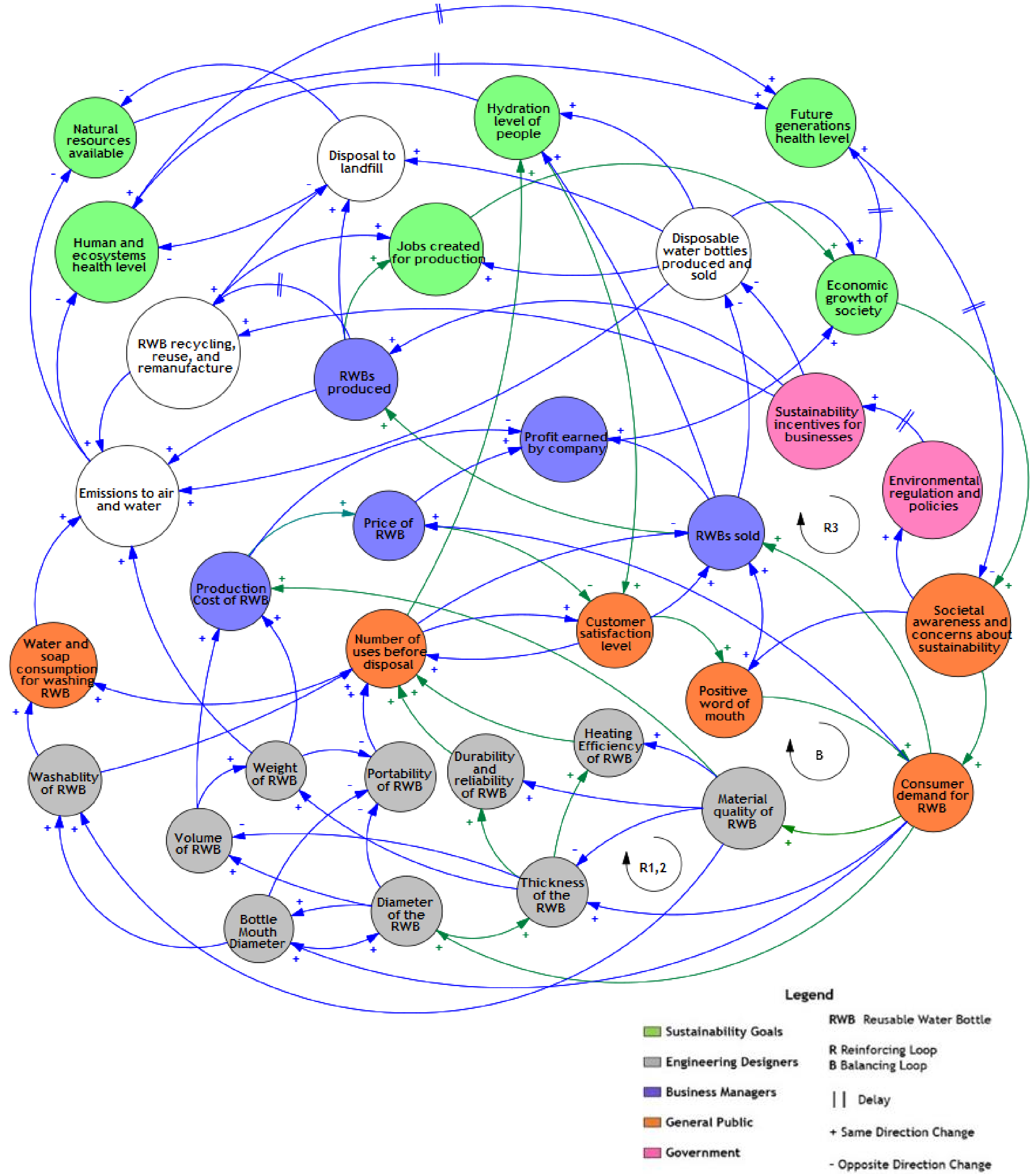

Fig. 3. Causal loop diagram (CLD) of the reusable water bottle (RWB) sustainable design

The elements associated with business managers lead to the profit (financial bottom line) that positively impacts economic growth, while its production depends on the government's incentives and regulations. The sales and the production of reusable water bottles are two critical points regarding the business managers group that can significantly influence the system. In addition, the government has regulations and incentives which are impacted by societal awareness and concerns about sustainability. These regulations initiate a process that can eventually achieve environmental, social, and economic sustainability. The sustainability incentives for businesses play an essential role in producing reusable water bottles and reducing the production of disposable water bottles.

The case study analyzed in this model has two end-of-life choices: disposal to landfill or recycled, reused, remanufactured. There are recyclability factors that are not included in the model since they are highly dependent on the materials selected for the reusable water bottle, and it is difficult to quantify material choices as measurable variables. Three reinforcing loops and one balancing loop are discussed here, marked in the CLD shown in Figure 3. The green arrows in the CLD show the loops discussed in this section.

The reinforcing loops 1 and 2 (R1,2) follow a similar pattern within the model and are marked together. The loop starts with consumer demand which may lead to an increase in the dimensions of the bottle, which positively changes the thickness of the bottle. The change in thickness then leads to positive changes in durability and reliability, and heating efficiency. All these factors are identified as different loops that increase the number of uses by the customer before disposal. Thus, the hydration level increases and provides more customer satisfaction, leading to an increase in word of mouth and consumer demand. These two reinforcing loops show that for this product system to reach its higher-level objectives, design features such as durability, reliability, and heating efficiency are essential to make the product more beneficial for the customer. The third reinforcing loop (R3) starts again with consumer demand, which increases the sales of reusable water bottles and therefore increases its production. The increase in production creates more jobs which positively changes the economic growth of society. As the economic growth of society increases, it provides more societal awareness and concerns regarding sustainability, increasing consumer demand. This reinforcing loop identifies the production and job market impacts vital to achieving economic sustainability within the system. The balancing loop (B) focuses on the material quality and price of the product. This loop starts with demand for higher material quality for the bottle, which will increase the production cost and consequently the final product's price. The price rise decreases customer satisfaction and the positive word of mouth, which feeds consumer demand. Therefore, the balance between material quality and price is critical because the material also defines the product's performance, but a significant price increase can negatively influence the customer's willingness to pay.

Based on the CLD generated for this complex system and three reinforcing feedback loops identified within the system, the leverage points that can significantly influence the change of behavior in this system are associated with the economic aspects of sustainability. This shows that society's economic growth helps achieve sustainable goals associated with social and environmental impacts. The importance of economic growth within the system is highlighted when it also leads to technological advancement, increasing the future generation's health level. The government's sustainability incentives significantly influence the system to create a shift by replacing disposable water bottles with reusable ones. In the general public domain, consumer demand and the number of uses before disposal are crucial regarding environmental and social impact considerations. A positive change in consumer behavior toward purchasing and using reusable water bottles is highly influenced by price and product utility features such as durability, reliability, portability, and heating efficiency. The engineering designers are tasked with finding the balance between the material quality, design parameters influencing these elements, and the weight and volume of the product. By focusing on the positive feedback loops within the system, the system can be impacted positively to create the transition toward sustainable design with a long-term horizon in mind and a holistic approach. Enabling sustainable product development can also be initiated through expanding the current LCA methods to consider the multi-domain interdependencies between social, economic, and environmental sustainability. Integration of the LCA, social life cycle assessment (S-LCA), and life cycle costing (LCC) analysis, can create the foundation of a holistic, sustainable design method that can be used to reveal the impacts of design decisions in product development.

6. Conclusion

In this research, the benefits of applying the systems thinking method toward the complex and multi-perspective problem of sustainability in design have been demonstrated using a reusable water bottle as a case study. The proposed method was divided into nine steps, which resulted in a system demonstrated as a causal loop diagram. The results from this causal loop diagram provide a comprehensive understanding of the system, revealing many improvement possibilities, trade-offs, and feedback loops (balancing and reinforcement) within the system. The interrelated dependencies between the system elements have been identified and analyzed. The analysis revealed the leverage points within the system that can improve the system's global sustainability objectives.

There are several limitations in modeling such complex systems using causal loop diagrams that can contain a certain level of complexity. The simplifications were necessary to capture a realistic version of the model, and several decisions were eliminated because of their unquantifiable features. The future work associated with this research includes quantifying the links between the elements of the CLD model and creating a system dynamics model that can reveal more in-depth information regarding the system's future behavior. Challenges are likely to arise in attempting to quantify each of the relationships in the CLD, which may inspire new primary research tasks. The current causal loop diagram can also be expanded to generate separate models that can address each dimension of this complex system and combine them to achieve a holistic, sustainable design perspective.

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