Sustainability Considerations in the Product Design Using System Dynamics and Fuzzy Cognitive Maps

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Abstract. Globally, sustainable product design is an issue that has been receiving more academic attention around the world. Understanding the sustainability-related design decisions seems to be important to ensuring sustainable design. Based on a stance, this study attempted to quantify sustainability factors in the product design through a hybrid method which combines the fuzzy cognitive mapping (FCM) and the system dynamics (SD) approaches. Designer behavior with regard to sustainability criteria was simulated in Vensim and sourced through sessions of two groups who deal with sustainable design. The results provide an easy-to-understand model of sustainable design to help designers analyze the dynamics of the cause-and-effect relationships between factors of sustainable design and long term scenarios, therefore, different scenarios at the inter and intra-cluster levels were built to determine the impacts of variable changes on the model developed.

Keywords: System dynamics (SD) . Fuzzy cognitive maps (FCM) . Sustainability

1 Introduction

In the last decade, sustainability has become an essential emphasis in product design; companies have been focusing on integrating environmental, (e.g., lifecycle issues and end-of-life recovery factors) and social (e.g., worker safety and health issues) concerns in addition to economic goals during the design process. Due to the critical environmental function of the sustainable design as an intermediary, this design plays an important role as one of the ecology's main pillars. The absence of a sustainable design affects all parts of the society, therefore, considering the issue of sustainable design is crucial for products and the overall society [7]. Indeed, Sustainable design is a complex issue with many quantifying factors to assume. The models proposed in the literature on the topic of sustainable product design offer some shortcomings in respect to the definition of variables and their corresponding cause-and-effect relationships. Researchers can not analyze holistically the dynamics of the factors of sustainable design through long-term analyses of the outcomes of changes in these factors.

Given these shortcomings, this study attempted to explore successful factors for sustainable design by using fuzzy cognitive mapping (FCM) and the system dynamics (SD) approach. There have been relatively few studies which examined the proposed hybrid approach in this paper, so the methodology contributes significantly to the existing literature on sustainability and design science. The variables required for the FCM and the data required for the dynamic analyses were gathered, and their cause-and-effect relationships were determined and mapped, in order to carry out the FCM and SD analyses. To determine the long-term outcomes of changes in the model variables, the mentioned information allowed for the definition of 4 scenarios with 8 simulations. These methods led to an easy-to-understand model that could aid designers to distinguish the variables that influence sustainable design and their long-term consequences. The rest of this paper is organized as follows. The next section provides a literature review of sustainable design. Section three presents the methodology. Section four provides the results of the dynamic system created.

2 Literature review

Sustainability objectives are being designed to measure performance, and to provide the feedback needed to promote improvement of design decisions. This refers to the idea that achieving current goals should be ensured by today's actions, while also achieving that future goals will not be hindered, and it is generally surrounds by three areas: economics, ecology, and society [3]. To enter ecological and social factors into the design decisions, it will be noticed that if the customers value such factors in their purchasing decisions or not. Consumer preferences for socially and environmentally sustainable products have been determined in the recent studies.

One tool for improving these effects is to enhance transparency which could help customers to make smart decisions [10]. The present paper thus attempt to introduce a fully cognitive structure that visibly portrays factors of sustainable design and determines the main factors impacting the implementation of conformant practices. Specifically, through the use of FCM and SD, this study sought to analyze factors of sustainable design in a dynamic manner that ensured a transparent rational analysis of the issue in question.

3 Methodology

In this paper, we show how system dynamics modelling can identify and portray the cause-and-effect relationships of material choice, tolerance and sustainability-related design decisions. Such the cause-and-effect relationships have been shown to affect future decisions and demand for each successive generation of products. By mapping the process, designers could increase understanding of the system level impacts of their decisions.

3.1 Fuzzy cognitive mapping

In practice, the phrase cognitive map based on [1], 'relates to models, depicting the structure of causal […] influences of portrayed situations, or systems'. This description stem from the common method that cognitive maps are an illustration of relationships between variables. These maps are a system of nodes and arrows, in which the direction of the arrows clearly indicated the causality between criteria [11, 14-23].

Kosko [9] was the first to discuss fuzzy cognitive maps (FCMs) according to [2], while also enhancing the power of cognitive maps through fuzzy values. The fuzzy logic of these maps is associated with how cause-and-effect relationships and their concepts can explain real values [12]. The primary difference between cognitive maps and FCMs is the way of demonstration of cause-and-effect relationships. FCMs use a plus (+) or minus (–) sign and a numerical value termed "weight" belong to the range [0.0, 1.0] or [−1.0, +1.0].

Figure 1 represents a graphical illustration of a FCM. In a simple FCM, as can be seen in Figure1, there are some nodes that stand for the concepts (C_i), of the modelled system. In addition, there are weighted arcs (W_{ij}) that connect concepts or nodes together, which show the casual relationship between concepts. In respect to the definition of concepts and their *cause-and-effect* relationships in FCMs, Ferreira et al. [4], explained that: 'These relationships can be illustrated by a positive and negative sign, and by a number from –1 to 1 that represents the intensity of the relationships.

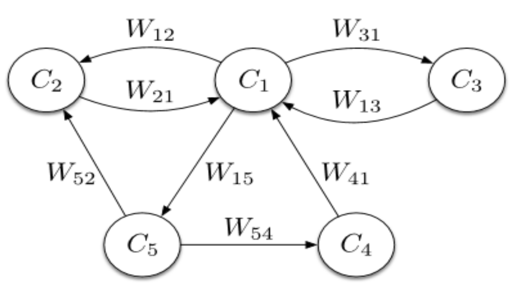

Fig 1. A simple FCM [13].

More specifically, all the values in the map can be fuzzy and, thus, each concept has a state value A_i that can be a fuzzy value in the range [0, 1] or within {0, 1}. In addition to, the weights of the arcs can be a fuzzy value within [−1, 1] or within {-1, 0, 1}'. In respect to the value of the cause-and effect relationships among concepts, one of three situations can be happend. According to [13], when the relationship is negative, $W_{ij} < 0$, when there is no relationship between two concepts, $W_{ij} = 0$, and when it is positive, $W_{ij} > 0$. The mathematical formulation of an FCM is represented by Eq. (1) [8 , 13]:

$$A_i^t = f(A_i^{t-1} + \sum_{j \neq i, j=1}^{N} A_j^{t-1} . \; W_{ji}) \tag{1}$$

in which A_i^t is the activation level of the concept C_i, in the t timeline; $f(x)$ is the activation function; and A_i^{t-1} is the activation level of the concept C_i, in the $t-1$ timeline. Also, A_i^t is the activation level of the concept C_j, in the t timeline, and W_{ji} is the corresponding weight related to the cause-and-effect relationship between concept C_j and C_i.

After each simulation, by using Eq. (1) and defining criteria's activation levels, new state vector with new values are obtained until the system reaches a fixed point that represents the system's equilibrium [4]. The management and modeling of complex dynamic systems can, therefore, advantage from the hybrid application of FCM and SD techniques and tools.

3.2 System dynamics

SD is a concept was introduced by [5, 6], which was initially related to the basic principles of systems theory. In this paper, the *cause-and-effect* relationships of sustainability-related design decisions have been portrayed through system dynamics modelling. Such relationships have been illustrated to affect future decisions, which decision makers could enhance understanding of the impacts of their decisions.

The proposed model was tested by running 8 simulations. Before the testing phase, different equations utilized in the stock-flow diagram are based on the primary features of FCMs and SD, where the value of a variable considers the value of the sum of all its *cause-and-effect* relationships. In respect to the clusters, an integral aggregation function of the sum of all their concepts' causality was used, divided by 100, to scale the model properly. A logarithmic function of the sum of all clusters' values was applied to stabilize the value of the head variable and keep the model scale appropriate. Finally, in respect to the variable of sustainable design, an integral function of the head variable value was applied to ensure, once again, the model was appropriately scaled. The initial performance values of the head variable, clusters, and sustainable design are located in Table 1.

4 Results

4.1 Dynamic analyses and results

The FCM and SD approaches identified three areas of concern, namely: (1) *Design specifications*; (2) *Maintenance requirements* and (3) *External Factors*. Regarding to the cognitive mapping techniques, this procedure was built on sessions with the designers as the decision makers. The first session comprised three steps, namely: (1) deciding factors of sustainable design; (2) creating clusters of factors; and (3) reorganizing the factors by hierarchical order of importance within each cluster. The entire procedure lasted for 4 hours.

Notably, all the information which used to create a collective cognitive map are based on the *Decision Explorer* software. This map, is shown in Figure 2. After the cognitive map was created, a second session was built to quantify the cause-and effect relationships in the cognitive map in order to develop an FCM. At the end of the second session, all the cause-and effect relationships had been determined, and this determination was the beginning point for a dynamic analysis of factors of sustainable design. This analysis allowed for the investigation of the long-term outcomes of cause-and-effect relationships. Therefore, using the Vensim software, a stock-flow diagram according to the FCM, presented in Figure 3.

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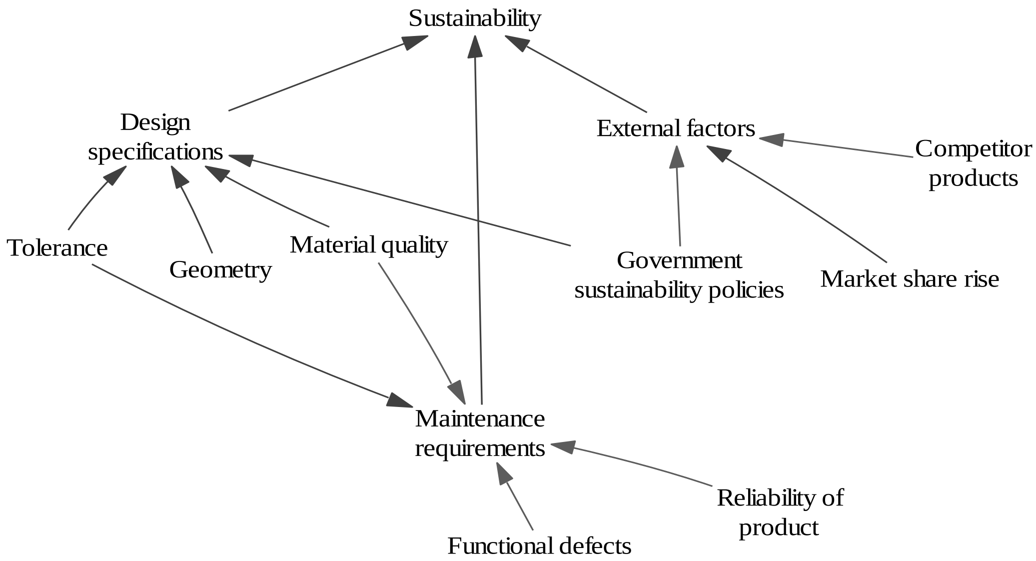

Fig 2. Collective cognitive map.

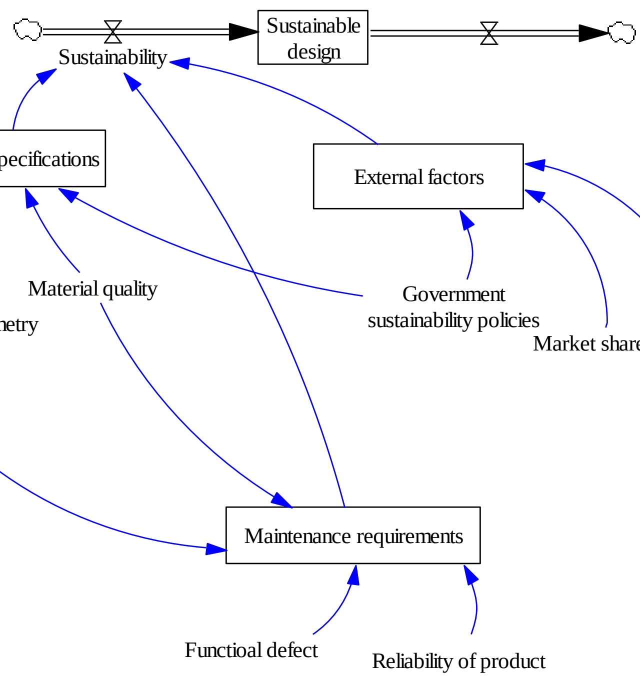

Fig 3. Stock and flow diagram of dynamics

Table 1. Initial performance values of clusters, head variable and Sustainable design.

Initial Performance	
Design specifications	16.50000
Maintenance requirement	10.20000
External Factors	8.90000
Head variable	4.70366
Sustainable design	3.72018

The inter-cluster analysis consisted of modifying the values of variables of the clusters to understand the outcomes for sustainable design. In the *Scenario1*, two simulations were built: (1) *Simulation 1*, with the values of the clusters influenced by a −0.3 change; and (2) *Simulation 2*, with a −0.6 change in the values of each cluster.

The initial cause-and-effect relationships are determined between the head variable and clusters, and those weights are located in Table 2. The outcomes for the head variable are found in Table 3. As apparent from Table 3, *Simulations 1* and *2* have a negative impact on performance in respect to the sustainability. These results also emphasize that *Simulation 2* has a more negative effect than *Simulation1* does, and this effect associated with the simulations' initial values. Thus, intra-cluster analysis, presented the alterations in each one of the clusters' criteria, according to the following tables.

Table 2. Weights of cause-and-effect relationships between head variable and clusters.

Determinant	
Design specifications	1
Maintenance requirement	1
External Factors	0.9

Table 3. Various values of sustainability in each simulation.

Determinant	**Simulation 1**	**Simulation 2**
Sustainability	−0.01738	−0.02113

Table 4. Various values in Simulations 3 and 4 for Scenario 2.

Determinant	**Weight of Relationship**	**Simulation 3**	**Simulation 4**
Tolerance	−0.90	-0.1	-0.1
Geometry	−0.90	-.06	-0.3
Material quality	1	-0.7	-0.5

Table 5. Various values in Simulations 5 and 6 for Scenario 3.

Determinant	**Weight of Relationship**	**Simulation 5**	**Simulation 6**
Functional defects	0.85	-0.4	-0.2
Reliability of product	1	-0.9	-0.6

Table 6. Various values in Simulations 7 and 8 for Scenario 4.

Determinant	**Weight of Relationship**	**Simulation 7**	**Simulation 8**
Government sustainability policies	−0.90	-0.4	-0.1
Market share rise	−0.90	-0.5	-0.3
Competitor products	1	-0.8	-0.4

Tables 4–6 related to each of the clusters and their corresponding scenarios. The long-term outcomes for the clusters resulting from the alterations presented above are shown in Table 7. As can be seen from Table7, *Simulation 3* has a greater negative long-term impact on the performance of the *Design specifications* cluster compared with *Simulation 4* because the simulation values illustrated in Table 4 are more negative. In addition, it can also be concluded that *Simulations 3* and *4* both have negative long-term effects on the performance of the *Maintenance requirement.*

Table 7. Long-term changes in clusters' values for each simulation

Cluster	**Simulation 3**	**Simulation 4**
Design specifications	-4.60	-3.20
Cluster	**Simulation 5**	**Simulation** 6
Maintenance requirement	-4.60	-2.80
Cluster	**Simulation** 7	**Simulation** 8
External Factors	-4.60	-2.90

However, *Simulation 5* has a much stronger negative impact. This is because the simulation values shown in Table 5 are also more negative in *Simulation 5*. The results for the performance of the *External Factors* cluster related to changes in the decision criteria, as shown in Table 6, are also clear in Table 7. The long-term outcomes are more negative in *Simulation 7* because, again, the simulation values shown in Table 6 are more negative compared with *Simulation 8*. Figure 4 and 5 highlight the long-term behavior for all simulations made in this study.

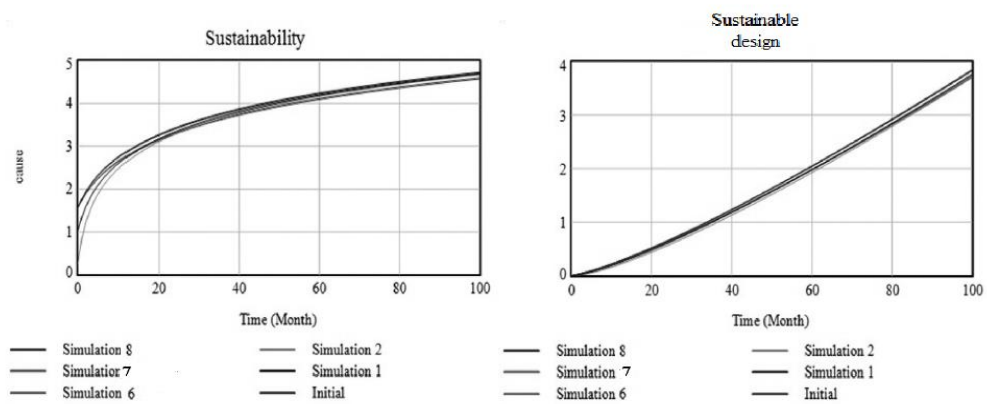

Fig 4. Long-term performance of sustainable design and head variable for their simulations.

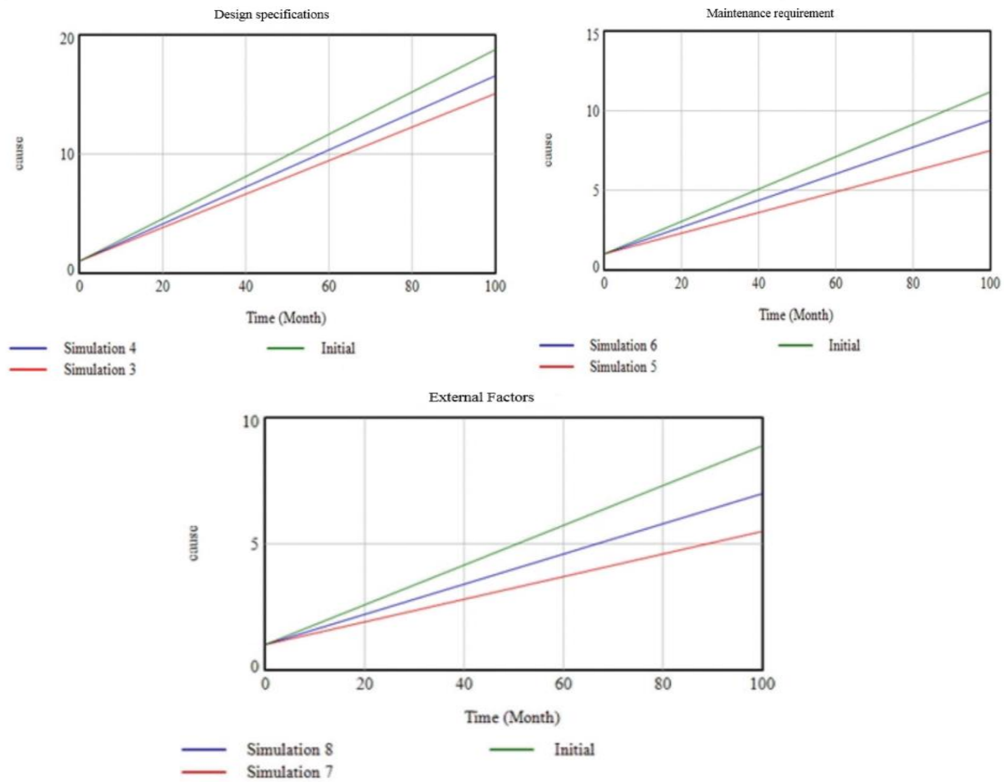

Fig 5. Long-term performance of clusters for their simulations.

The integrated use of FCM and SD, presented the identification of factors of sustainable design and the ways they correspond with each other. The designers as stakeholders must analyze and understand these changes in order to make more informed decisions. All these factors can impact sustainable product design evolution during the time, so designers require to analyze possible variations of the proposed process and seek sustainable attitudes in their designs.

5 Conclusion and Future Research

The results of the present paper goes beyond the current approaches because it overcomes some shortcomings by considering a number of variables that influence sustainable product design and the cause-and-effect relationships in the FCM. Additionally, the proposed model provides dynamic analyses through SD, which illustrate and map the behavior of variables over time and the changes that can affect sustainability. Through such a model, designers can change variables of the models to create different scenarios. This approach can help those decision makers make more conscious decisions and understand the magnitude of this trade-off.

For future research, it is recommended to use other ways of investigating the issue of sustainable design, and evaluating tradeoffs among factors while enriching the beneficial for precious insights. Additional studies may also assume performing a greater a cluster's number of factors, the larger number simulations and scenarios because this could lead to another conclusions.

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