A Model of the Sustainability Requirements Dynamics for New Product Development

Marios Bisilkas
Universitat Jaume I
12071 Castellón de la Plana, Spain
al244114@alumail.uji.es

Ivan Barreda Tarrazona
Universitat Jaume I
ivan.barreda@eco.uji.es

Aurora Garcia-Gallego
Universitat Jaume I
mgarcia@eco.uji.es

Abstract

The purpose of a product is to satisfy the needs of the people that are going to acquire it. In order to do so, it has to incorporate characteristics and features that fulfill a series of requirements set by users' expectations and external conditions. In this essay, we are focusing on the design process of a new product and examine up to what extent should sustainability considerations as defined from the triple bottom line should be incorporated and when. Results indicate that the most important factors are the reaction of the customers to the sustainability performance of the product and its price. Attention needs to be paid though, as early incorporation can provide either a competitive advantage or considerably hurt profitability. Finally, we discuss effective policies that could induce a permanent shift towards more sustainable operations.

Keywords: New Product Development, Sustainability, Profitability, Triple Bottom Line, Product Design

1 Introduction

The purpose of a product is to satisfy the needs of the people that are going to acquire it. In order to do so, it has to incorporate characteristics and features that fulfill a series of requirements set by users' expectations and external conditions. Sustainability is an aspect that is expected to heavily influence both these requirements and expectations (Souza et al, 2009). In this essay, we will be focusing on the design process of a new product, as that is the moment when all specications of the product are decided and the ability of the product to satisfy current and future requirements are set.

For a product to be introduced in a market it needs to comply with existing regulations. These regulations determine minimum specifications for a variety of features, such as materials usage, generated emissions, waste and noise levels, energy consumption and safety (accident prevention). The minimum specifications are based on scientific knowledge and are usually a result of discussions among scientific and industry experts, politicians and the local community. New regulations are commonly accompanied by transition periods, during which older specifications are still tolerated or products' characteristics can be gradually updated until they reach the final target. Therefore, they can be viewed as the terminal date up to which older products can still exist in the market or in operation in the hands of the users. Non-compliance with the regulation can both prevent a product from being introduced in the market, if identified in advance, and lead to important penalties in forms of fines.

Customers' expectations regarding a product's performance may vary substantially, depending on their previous individual experiences with similar competitors' products or different products from the same manufacturer. On one hand, bad experiences are in favor of a new product, as they create the sense of advanced features, while good experiences may have the opposite effect, as they raise the bar of comparison. On the other hand, bad experiences may prevent a customer from acquiring the product even if it is obviously superior to a competing one, while good experiences can influence positively the comparison even when the product is clearly inferior in characteristics.

The price of a product is another factor that affects the expectations of the customers, as higher priced products are expected to perform in proportion to the price difference with its competition.

Companies produce products in order to gain financial benefit from their operations. A new product is expected to contribute to this cause; it needs to provide sufficient profit margin that will justify inversion in its production. Enhanced characteristics have to be accompanied by a cost-benefit analysis that demonstrates the benefit of incorporating them. In a similar manner, the product characteristics need to be aligned with the characteristics of the market it will be introduced in. A better product will satisfy more customer segments in terms of performance, but its increasing price may make it improbable to be acquired by the price-sensitive customers.

Enhanced characteristics of a new product can be proved to be a means of competitive advantage; by improving the performance of a product the company can drive the comparison of competing products to be based on the aspects the company is strong at. This technique, however, needs to be used with caution. Higher performance creates stronger expectations for the following products; customers get accustomed to enhanced characteristics and expect that those will be present at all times in the future. Failure to do so needs to be justified by a reduced price, which hurts the profit margin. In essence, a form of trap is created, locking-in the expected company performance from customers' side.

Even though these, mainly financial, tradeoffs are true for any product, sustainability awareness adds another important aspect: the needs of the the society. Environmental and social conditions affect the importance of the tradeoffs described above and can mitigate or multiply the effect of each and every one of them, leading to new points of balance. For example, we can think of the case where, because of earlier negligence, environmental protection becomes the crucial decision variable for customers: then the price of the product becomes irrelevant, as the environment needs to be protected at any cost. A similar effect comes from the technological constraints. As technology improves, the tradeoffs are moderated and improved performance goes along with low costs and market penetration.

As people become more aware of the sustainability problem, they will require that products incorporate features that alleviate their concerns. Following this line, we will be examining the requirements of sustainability that a new product should incorporate, in accordance with the expectations created by the environmental, social, market and technological conditions. The way or the mechanisms through which the market reacts to sustainable practices is a field that has not attracted much attention (Kassinis and Soteriou, 2003). The elicitation of customer involvement in the firms' environmental efforts can provide interesting managerial insight.

The implications of ecologically sustainable development for corporations has begun to appear in the literature in the last 15 years. Concepts of total quality environmental management, ecologically sustainable competitive strategies, technology transfer through technology-for-nature-swaps, and reduction of the impact of populations on ecosystems are articulated (Shrivastava, 1995). Sustainable development pressures have increased complexities and present ambiguous challenges that many current environmental management techniques cannot adequately address. Sustainability is an integrated web; a multilevel and multisystem perspective is necessary (Starik and Rands, 1995). The implications for ecological sustainability of simple dyadic relationships between the organization and entities at the individual, organizational, political-economic, social-cultural, and ecological environment levels have been examined. Recent research provides a background to better understand current trends in this multidisciplinary field that intersect with operations management and the research opportunities and the challenges it presents (Linton, Klassen and Jayaraman, 2007). The problems of integrating sustainable development concerns in the supply chain, and specifically the applicability of life cycle assessment should be examined drawing on complexity theory, risk management, stakeholder theory and the innovation dynamics literature (Matos and Hall, 2007).

Essential to developing sustainable products is sustainable design. The early history of product design is replete with examples of inefficiency over its total life-cycle. As the ratio of labor costs to material costs went up, it became uneconomical to replace or repair most products individual parts, and their designs reflected that. The solution to most malfunctions or breakdowns was simply to replace the entire assembly or subassembly. Manufacturers are now moderating this practice, developing designs that avoid environmentally hazardous components and make it economically possible to save components that have high reuse value. Modular designs increasingly facilitate remanufacturing, automated diagnosis of problems, and repair or part replacements by users, original manufacturers, and third parties (Chen, Navin-Chandra, and Prinz 1994; Ferrer and Whybark 2001; Guide and Van Wassenhove 2001; Krikke, Bloemhof-Ruwaard, and Van Wassenhove 2003). Frameworks for designing conventional products can be modified for designing green products.

For example, Singhal and Singhal (2002) developed a framework for analyzing compatibility in modular product design that is analogous to analyzing compatibility of product designs for recyclability and reuse (Di Marco, Eubanks; Ishii 1994).

Operations Management (OM) science is attempting to use the tools and concepts of lean operations to add green metrics to the measures of excellence companies use in evaluating business processes. Several OM authors have written about whether the lean and green approach is evident in practice, how best to achieve it, and what its net benefits are. Mitigating environmental, health, and safety impacts of a company is socially responsible and good business. Promoting environmental care can enhance a company's and an industry's image (Chinander 2001) as shown by chemical industries adoption of codes of responsible care and the rapid spread of ISO 14000 (Angell 2001; Corbett and Kirsch 2001, 2004; Vastag 2004). Kassinis and Soteriou (2003) show that environmental practices in the hospitality industry enhance profitability by improving customer satisfaction and loyalty. Improved environmental, health, and safety performance can aid plant-level productivity efforts (Klassen 2001) and increase revenues and market share (Delmas 2001, 2004). To gain these positive results, the firm must establish management systems and tools that integrate environmental, health, and safety metrics with other process metrics within the company and across the supply chain (Bowen et al. 2001). King and Lenox (2001) and Rothenberg, Pil, and Maxwell (2001) examined the links between lean manufacturing and green manufacturing and found some synergies, but also found that harvesting them is not simple. People generally assume that improving quality practices improves environmental performance; Pil and Rothenberg (2003) suggest that the causality can also work in the other direction, with improvements in environmental practices leading to improvements in quality. Sroufe (2003) analyzed the link between environmental management systems, environmental practices, and operational performance and found that this link is substantially stronger for some practices than for others.

To comply with regulations, companies must track their use of hazardous substances and emissions of pollutants. Because regulatory scrutiny is costly, many companies are going beyond compliance (XL and 33/50 programs in the U.S. and other voluntary programs elsewhere; Rothenberg, Pil, and Maxwell 2001). By going beyond current regulations, companies reduce the costs of changing technologies and operating policies to comply with new regulations (Woensel, Creten, and Vandaele 2001 and Delmas 2001, 2004).

Another factor driving companies to improve their environmental performance is the risk of being held liable or found negligent for accidents or environmental damage, a risk they face even when they act prudently and use stateof-the-art technology. To limit liabilities, many companies implement strict risk-reduction mechanisms, lowering the levels of pollution, biocides, and toxics associated with their supply chains and products (Snir 2001; Wolf 2001; Kleindorfer and Saad 2005).

This essay focuses on the interaction between the design of a product and the sustainability considerations of the customers. We present a dynamic hypothesis model, which will incorporate the concepts of:

- how does public awareness of the need for "design for sustainability" influence the development of a new product, and
- how can product design help build public awareness of the need for sustainability

The resulting dynamic hypothesis can be articulated as follows: *the sustainability performance of a new product depends on the public awareness of the sustainability problem as expressed by existing legislation and tacit expectations and concurrently sets the ground for forming the expectations regarding future performance.* The study follows in the tradition of research in organizational learning and adaptation showing how organizational behavior arises from the interactions of physical and institutional structures with boundedly rational decision making, often leading to unintended and dysfunctional outcomes (e.g., Barnett and Hansen 1996, Forrester 1961, Levinthal and March 1981, March 1991, Masuch 1985, Sastry 1997, Sterman et al. 1997). We go beyond most existing studies, however, by developing a formal model that provides a tool to design and test policies to avoid or reverse the undesirable outcomes generated by existing structures and routines. The paper follows our research approach. First, we developed a formal model that integrates the structural elements of client interaction settings (2). We tested the model following the guidelines of the System Dynamics methodology (3). We then used the model to understand the sources and implications of public awareness on sustainability (4) and generate some policy recommendations that could induce a permanent shift towards sustainability-focused operations. (5). Finally, we discuss the implications of our findings for organizational theory and the production industry in general, and identify future research areas.

2 Model Structure

In this section, we present a formal model that integrates the characteristics of a customer focused market. The model allows us to test whether the awareness-sustainability interrelationship can be explained from structural elements of the service - delivery process - physical flows, organizational structure, and decision making - as opposed to variations unique to particular settings. Theoretical foundations and evidence for the hypothesized causal relationships are presented with each model equation.

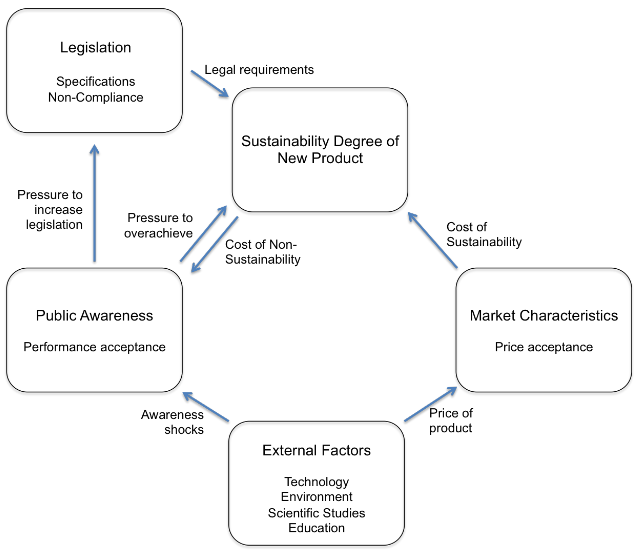


Figure 1. Model Structure Overview

The model consists of three sectors (*Figure 1*). The *sustainability degree* sector tracks the sustainability performance a new product should incorporate as the best response to external and internal factors. Service demand and standards determine the required service capacity. The *market response* sector models clients' acceptance or rejection of the proposed solution the product represents, depending on its sustainability performance and price. Finally, the *awareness* sector tracks the perception and formation of expectations regarding the sustainability performance and models the impact of expectations and public awareness on legislation. We assume that firms operate in an economically efficient manner: they will only engage in the design of a sustainable product if the cost of not doing so overcomes the increased cost of sustainable production. This approach is in line with the existing literature that suggests that operating in a sustainable manner yields operating efficiencies and can be a source of economic profitability (Clelland, Dean and Douglas, 2000; King and Lenox, 2002; Russo and Fouts, 1997).

Sustainability degree. The sustainability degree sector tracks the performance in terms of sustainability the new product should incorporate and determines the cost of production and the portion of the market the product addresses to. The sustainability degree (α) increases by new legislation (SL) and public pressure to overachieve (PO), while it is reduced when the cost of being sustainable (C_s) becomes higher than the cost of being non-sustainabile (C_{ns}).

$$(d/dt)\alpha \quad = \quad \alpha_i - \alpha_o \tag{1}$$

The sustainability degree increase rate is the sum of changes needed because the product does not comply to existing specification legislation (SL), of changes driven by the pressure to overachieve (PO) and of changes to decrease the cost of non-sustanability, while the sustainability degree decrease rate becomes positive only when there exists a need to decrease the cost of sustainability.

$$\alpha_i = \begin{cases} SL - \alpha & \text{if } SL > \alpha, \\ 0 & \text{otherwise} \end{cases} + \begin{cases} 0.001 & \text{if } C_{ns} > C_s, \\ 0 & \text{otherwise} \end{cases} + \begin{cases} 0.001 & \text{if } PO > 0, \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$\alpha_o = \begin{cases} 0.001 & \text{if } C_s > C_{ns}, \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

Market response. The market response sector models the reaction of the customers to the characteristics of the product, both in terms of sustainability performance and price of acquisition (p). Different customers will have different expectations regarding the performance of the product and will only consider a proposal that meets their expectations (S_{acc}); similarly, they will have different acquisition power and they will only consider products that they can afford (p_{acc}). For the shake of simplicity, we assume that for any

α	Sustainability degree, normalized to 0-1
α_i	Sustainability degree increase rate
α_o	Sustainability degree decrease rate
C_s	Cost of Sustainability
C_{ns}	Cost of Non-Sustainability
C_p	Cost of Producing one unit
D	Delay for new experience to be converted to expectation
d	Delay for pressure rates to be realized
E	Environmental Incidents
F	Fines for not meeting Specifications Legislation
H	History of performance experienced
M	Market size, normalized to 100
MC	Market Captured; percentage of the market served
N	Product's compliance to customers' expectations
NCL	NonCompliance Legislation
p	Price of product
PL	Pressure to Increase Legislation, normalized to 0-1
PL_i	Pressure to Increase Legislation increase rate
PL_o	Pressure to Increase Legislation decrease rate
PO	Pressure to Overachieve, normalized to 0-1
PO_i	Pressure to Overachieve increase rate
PO_o	Pressure to Overachieve decrease rate
S_{acc}	Access to the market provided by the sustainability performance
p_{acc}	Access to the market provided by price
SL	Specifications Legislation, normalized to 0-1
SL_i	Specifications Legislation increase rate
SL_o	Specifications Legislation decrease rate
T	Top Standards regarding performance experienced
U	Customers' expectations
W	Public Awareness of the Sustainability problem
π	Profit Margin per unit of product
Ω	Scientific Research

Table 1. List of variables used

level of sustainability degree and price (p), the final portion of the market a product addresses to is the minimum of the two; if a product performs well enough for 60% of the potential customers but only 40% of all customers can afford the price, then the product can serve only 40% of the market. The model can be changed in order to account for the possibility of different (or even random) overlapping, by using different percentages of overlapping (equal to the probability of wanting to buy the product multiplied by the probability of being able to afford it), but the intuition still holds.

$$S_{acc} = f(N, \alpha) \tag{4}$$
$$p_{acc} = f(p) \tag{5}$$
$$N = \frac{\alpha}{U} \tag{6}$$

where N is compliance of the product's performance to customers' expectations, normalized with values between 0-1, and U being the value of these expectations. The cost of sustainability corresponds to the lost profit because of price rejection, while the cost of non-sustainability corresponds to the lost profit because of performance rejection and the cost of possible fines F because of non compliance with the existing legislation regarding specifications.

$$C_s = \begin{cases} (S_{acc} - p_{acc}) \cdot M \cdot \pi & \text{if } S_{acc} > p_{acc}, \\ 0 & \text{otherwise} \end{cases} \tag{7}$$
$$C_{ns} = F \cdot MC \cdot M + \begin{cases} (p_{acc} - S_{acc}) \cdot M \cdot \pi & \text{if } p_{acc} > S_{acc}, \\ 0 & \text{otherwise} \end{cases} \tag{8}$$
$$MC = min\{S_{acc}, p_{acc}\} \tag{9}$$

The cost of fines (F) is function of the non-compliance legislation (NCL) and the distance between the actual performance from the specifications legislation; the more a product violates existing legislation, the higher the corresponding fines will be. On the other hand, price (p) is the sum of the cost of production (C_p) and a fixed profit margin (π); we use a fixed profit margin in order to see the pure effect of the increased environmental performance on the final price of the product, that could otherwise be mitigated from a lower profit margin. Finally, the cost of production is a function of the sustainability degree of the product.

$$
\begin{aligned}
F &= NCL \cdot f(SL - \alpha) && (10) \\
p &= C_p + \pi && (11) \\
C_p &= f(\alpha) && (12)
\end{aligned}
$$

Awareness. The awareness sector tracks people's perception of the sustainability problem and the formation of expectations regarding the sustainability performance of new products, as well as models the impact of expectations and public awareness on legislation. Public awareness (W) is modeled as a stock that increases over time, when certain circumstances happen. First, scientific research (Ω) advances our understanding about current and future consequences of our actions and the need to protect the environment; secondly, environmental incidents (E) that occur unexpectedly (i.e. an oil spillage, a nuclear explosion, etc.) accelerate - even if sometimes temporarily - people's consideration of products' environmental performance; finally, past increased performance is transformed into an expectation over time (with a delay (D)).

$$
\begin{aligned}
(d/dt)W &= W_i && (13) \\
W_i &= \Omega + E + \begin{cases} \frac{T-W}{D} & \text{if } T > W, \\ 0 & \text{otherwise} \end{cases} && (14) \\
\Omega &= f(t) && (15) \\
E &= f(t) && (16) \\
T &= max\{\alpha, H\} && (17) \\
U &= W && (18)
\end{aligned}
$$

As public awareness increases, it creates pressure to increase current legislation (PL) and to overachieve (PO). The pressure to increase legislation raises by the differences between current awareness with current specifications legislation and current sustainability degree; once it reaches a certain threshold, part of it gets released by increasing the specifications (SL_i).

$$(d/dt)PL = PL_i - PL_o \tag{19}$$

$$PL_i = \begin{cases} \frac{W-\alpha}{d} & \text{if } W > \alpha, \\ 0 & \text{otherwise} \end{cases} + \begin{cases} \frac{W-SL}{d} & \text{if } W > SL, \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

$$PL_o = \begin{cases} \frac{PO}{d} & \text{if } PO > 0.8, \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

Similarly, as public awareness grows, it increases the pressure on the company to overachieve; to perform beyond minimum specifications. When a certain threshold is passed, the pressure is released by increasing the sustainability degree of the new product.

$$(d/dt)PO = PO_i - PO_o \tag{22}$$

$$PO_i = \begin{cases} \frac{W-\alpha}{d} & \text{if } W > \alpha, \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

$$PL_o = \begin{cases} \frac{PO}{d} & \text{if } PO > 0.4, \\ 0 & \text{otherwise} \end{cases} \tag{24}$$

Finally, the specifications legislation (SL) increases when the pressure to increase legislation is released, and remains on the same levels until the next release; similarly behaves NonCompliance Legislation.

$$(d/dt)SL = SL_i \tag{25}$$

$$SL_i = \begin{cases} \frac{0.05}{d} & \text{if } PL_o > 0, \\ 0 & \text{otherwise} \end{cases} \tag{26}$$

$$(d/dt)NCL = NCL_i \tag{27}$$

$$NCL_i = \begin{cases} \frac{1}{d} & \text{if } PL_o > 0, \\ 0 & \text{otherwise} \end{cases} \tag{28}$$

3 Model Validation

Validation of simulations models in general and Systems Dynamics (SD) models in particular consists of two types of validity tests (Barlas, 1989):

1. Structural validity tests: the function of which is to check whether the structure of the model is an adequate representation of the real structure. Structural validation is typically achieved in two parts:

   - by comparing the model equations with the real system relationships ("empirical" structure validation)
   - by comparing the model equations with the available theory ("theoretical" structure validation)

2. Behavior validity tests: the function of which is to check if the model is capable of producing an acceptable output behavior. Behavior validation is also typically achieved in two parts:

   - tests to determine whether the behavior patterns generated by the model are close enough to the major patterns exhibited by the real system
   - examining the model behavior under different conditions, try to determine whether there is a major error in the structure of the model (extreme conditions)

The heart of a system dynamics model is a dynamic hypothesis that is illustrated by the structure of the model. The purpose of the dynamic hypothesis is to explicitly articulate how structure and decision policies generate behavior. A well formulated hypothesis needs to be (1) logically sound, (2) grounded in previous knowledge and (3) empirically testable. Furthermore, it must also say something interesting about the real world; it must be relevant - logic and consistency alone are not enough (Oliva, 2003). Models are built in order to understand an observed behavior and provide guidance on when does this behavior occur and the conditions under which it may be altered. The focus lies on the purpose of the model, not the model itself. Sterman (2000) provides and excellent guide to model validation; we provide a brief description of its main aspects and the corresponding results for our model below:

Boundary adequacy. The purpose of the boundary adequacy test is to examine whether the important concepts for addressing the problem are endogenous to the model. Indeed, the model incorporates analytical description of the public awareness creation process and the generation of new legislation both for minimum specifications and non-compliance. We have also incorporated the reaction of the market to the proposed configuration of a new product, both in terms of performance and price. In order to check for the adequacy of the system boundaries, we have modified the model to include plausible additional structure (i.e. R&D expenditure as a function of revenue in order to invest in new technologies that alter production costs), made constants and exogenous variables endogenous, and repeated the sensitivity and policy analysis. The results indicated that by doing so the observed behavior of the system does not change significantly, apart from the timing of events, as expected.

Structure assessment. Testing the model structure consistency with the relevant descriptive knowledge of the system can be quite cumbersome, since our knowledge of the system behavior is limited; this limitation was one of the reasons motivating the current study. We have chosen to aggregate individual actors of the system (customers) into generic groups with common behavior and have approximated their individual preferences within the groups using probability distributions to describe their possible decisions when faced with the opportunity to acquire the new product. In addition, we tested the model in parts, to check for its consistency under different assumptions.

Dimensional consistency. We have examined that all equations are dimensionally consistent without the use of parameters having no real world meaning. We have used parameter values with real world counterparts, based on experts opinions and archival material and have conducted extreme conditions tests to check for unreasonable outputs when inputs take on extreme values, both alone and in combination. Finally, we subjected the model to large shocks caused by extreme values in random variables and different numerical integration methods.

Behavior reproduction and sensitivity analysis. We have examined the model for its ability to reproduce the behavior of interest and to endogenously generate the symptoms of difficulty motivating the study, namely the creation of public awareness stemming from the sustainability performance of existing (or past) products and, in turn, the influence of public awareness on the design of new products. We also tested that the model generates the behavior observed in other instances of the same system, particularly when these interactions are neutralized and its ability to successfully anticipate the response of the system to novel conditions. Univariate and multivariate sensitivity analysis allowed us to examine whether the numerical values, generated modes of behavior or policy implications vary significantly when assumptions about parameters, boundary and aggregation are varied over the plausible range of uncertainty, as discussed in the next paragraphs.

4 Analysis: implications of public awareness on sustainability

In order to gain confidence in our model, and its ability to reach equilibrium, we first test a reduced version of it, without the interaction between sustainability performance and public awareness. The equilibrium in this case corresponds to the optimal solution for the new product's configuration given existing legislation and market conditions. For reasons of simplicity, we assume that both sustainability acceptance and price acceptance distributions of all of clients are uniform; each client is equally likely to be highly or poorly sensitive to the sustainability performance of the product and its price. *Figure 2* offers a graphical representation of the relationships between S_{acc} and α, p_{acc} and p, C_p and α, and finally F and $(SL - \alpha)$. This assumption, along with the following values for existing legislation will constitute a base case scenario for this analysis: $D = 60$, $d = 1$, $F = 4$, $M = 100$, $SL = 0.2$, $T = 0$, $W = 0.2$, $\pi = 5$.

The results of the reduced model analysis can be found in *Table 2* and their graphical representations in *Figure 3*. The sustainability degree for the base case scenario settles at the value of 0.5874, much higher than legal requirements (0.2); this indicates that it is best for the company to create highly performing products as the market recognizes and awards such efforts. We compare this result against two extreme scenarios: one where clients are insensitive to price, indicating that price variations for the product are not significant for clients' final decision of acquiring the product or not, and a second where clients are insensitive to the sustainability performance of the product, indicating that clients do not consider its performance significant, but heavily base their decision on its price. The model reproduces the expected behavior for both cases. For the price insensitive clients scenario, the

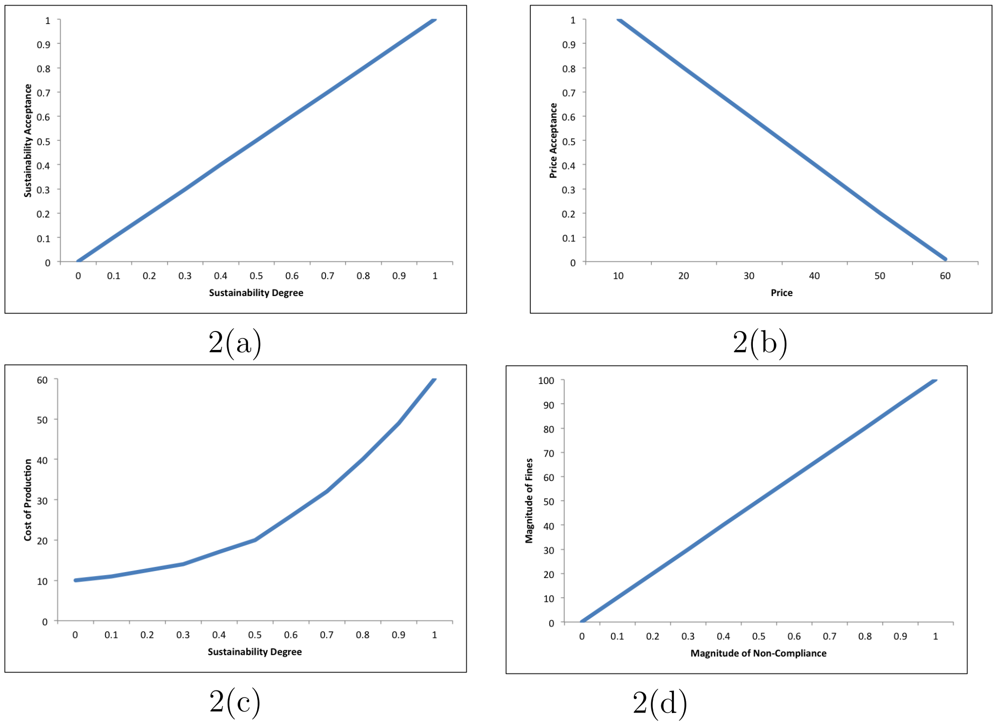


Figure 2. Relationships among key parameters

equilibrium value for the sustainability degree is 1, corresponding to a fully sustainable product; the company designs a product that will attract even the most demanding customer. On the other hand, for the sustainability insensitive clients scenario, the equilibrium value for the sustainability degree is, as expected, very close to the specifications described by legislation (0.1990); in the specific case, it is optimal for the company to design a product that even slightly violates legislation, as the expected fines from doing so are lower than the additional cost of complying with them.

Figure 4 offers a graphical representation of the values over time for some of the main parameters in the model: sustainability acceptance by the market (4a), price acceptance by the market (4b), cost of non-sustainability (4c) and cost of sustainability (4d). We have run the simulations long enough in order to allow the system to reach equilibrium, after which no changes are observed. In the base case scenario, S_{acc} increases steadily over time until it reaches levels of about 59% where it stabilizes, while for both price and

Parameter	Base Case	Price Insensitive	Sustainability Insensitive
α	0.5874	1.0000	0.1990
Sacc	0.5876	1	1
pacc	0.5876	1	0.822
Cns	0	0	32.89
Cs	0	0	88.9

Table 2. Simulation results for the reduced model

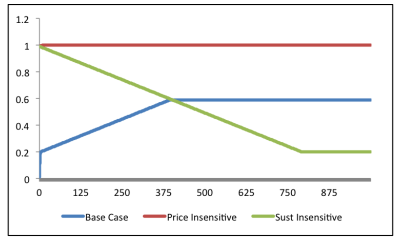
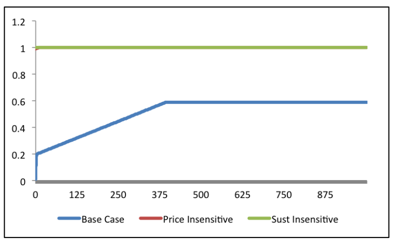
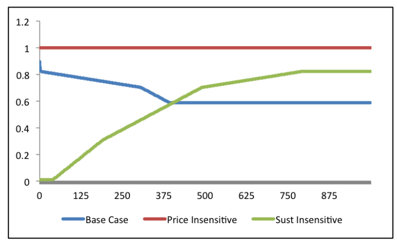


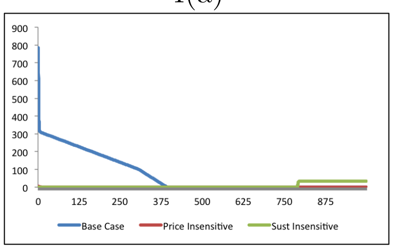
Figure 3. Sustainability degree equilibriums for the reduced model



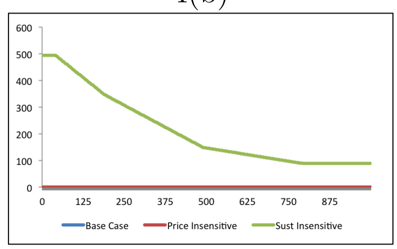
4(a)



4(b)



4(c)



4(d)

Figure 4. Results of the reduced model

sustainability insensitive clients scenarios, it reaches the maximum value of 100%. p_{acc} follows a different trend, decreasing at levels of about 59% from the initial 100% in the base case scenario. For the price insensitive clients scenario, its value remains stable at maximum levels of 100%, as expected, since price is irrelevant to clients' decision making process. On the other hand, under the sustainability insensitive clients scenario, the value of p_{acc} increases from minimum levels of 0% to about 82%. On the contrary, C_{ns} reaches a similar equilibrium under all three scenarios, at minimum (or almost minimum) levels; the small difference for the sustainability insensitive clients scenario is due to the fact that the optimal response of the company is to design a product that violates minimum legal requirements of specifications, and therefore incurring costs of fines. Finally, C_s follows a similar path for the first two scenarios, with its value to be at minimum levels, while its behavior variates substantially in the case of the sustainability insensitive clients scenario where even though it initiates in large values, it decreases over time with a decreasing rate, until it stabilizes at a low value. This low value is a result of the fact that clients request a product with zero sustainability performance, and therefore, any cost for performance above that level is considered a mere expense.

The results of the simulations are in line with the expected theoretical results of the underlying scenarios, providing us with confidence that the model is suitable in order to examine the real influence of public awareness of the sustainability problem on the values of the sustainability degree parameter that represents the best response of the company to existing legislation and market conditions. We run a collection of different scenarios, including the ones used for the reduced model, and provide comparisons when appropriate. Scenarios 2-9 described below are simple variations of the base case in order to understand the influence of each parameter in the final outcomes.

Scenario 1: Baseline. The base case scenario is identical to the one described in the previous section of the reduced model; we briefly remind the assumption that both sustainability acceptance and price acceptance distributions of all of clients are uniform, and that the values for the secondary parameters are: $D = 60$, $d = 1$, $F = 4$, $M = 100$, $SL = 0.2$, $T = 0$, $W = 0.2$, $\pi = 5$.

Scenario 2: Price Insensitive clients. In the price insensitive clients scenario, we assume again that clients do not take into consideration the price of the product when faced with the decision to acquire it or not: their only consideration is whether the product satisfies their personal expectation of performance in terms of sustainability.

Scenario 3: Sustainability Insensitive clients. In the sustainability insensitive clients scenario, as in the previous section, we assume that clients do not care about the sustainability performance of the product and base their purchase decision entirely on the price.

Scenario 4: Environmental Shock. The history of human interaction with the environment is full of negative incidents caused by ignorance and/or negligence. The magnitude of these incidents vary in importance and affected area, ranging from local problems that can be confronted with local measures (pollution of a lake), to global problems that require cooperation among people in a large part of the world (global warming). For this scenario, we will consider mainly incidents that occur locally but have a global effect; examples from the recent history include BP's oil spillage in the Gulf of Mexico (2010) and Fukushima's (Japan) nuclear leakage (2011) that have caused a sudden increase in people's awareness regarding the consequences of human activity on the environment. We model this case as an momentary increase of the value of E, that returns to its original values right after; the environmental shock will cause an increase of W by 10 percentage points.

Scenario 5: Research Studies Shock. Scientific research over the last few decades increasingly focuses on the effects of human activities on the environment. Case studies of past incidents shed light on the causes of occurrence and increase our understanding of the consequences of our actions and the need to find alternative ways of operating. Furthermore, it allows for a more accurate prediction of future consequences under current ways of action, promoting new measures and regulations. We model the effect of scientific research as a repeated momentary increase of the value of Ω over fixed intervals.

Scenario 6: Technology Shock. Technology plays an important role in the equilibriums that are formed throughout the marginal analysis process, as it directly affects the cost of production for the new product. Emerging technologies promise to reduce the cost of producing better performing products in terms of sustainability and therefore allowing for previously price restricted customers to gain access to them. Since a technological breakthrough cannot be scheduled - its magnitude and timing are highly uncertain - we model two cases: a breakthrough that reduces the cost of current technology by half in an early stage (6a) and in a late stage (6b).

Scenario 7: S-shaped acceptance functions. In this scenario we relax the assumption that potential customers are uniformly distributed regarding their ability to afford the new product and their expectations for its performance. Instead, we use normal distributions for both acceptance parameters, that result in s-shaped functions for S_{acc} and p_{acc}. The normal distribution corresponds to the belief that most customers will behave in a manner close to the average behavior, while few will be outliers in each direction (extremely or poorly sensitive).

Scenario 8: Education to reduce thresholds. A social planner can intervene in the decision process of the potential customers through education. This social planner needs not be a governmental actor, but may as well be a non-governmental organization, like an association of customers. Informative events in schools, neighborhoods or advertising through public media can influence both public awareness and the pressure to increase legislation. We model this intervention by a reduction by half on the thresholds for pressure to be released.

Scenario 9: Subsidies for overachieving. The government can influence the company's decision on the design of the new product by influencing the design process towards better performing products. Such an intervention can be achieved using subsidies that reward innovation and overachievement; in this scenario, we model this intervention using an increasing subsidy in accordance with the difference between legal requirements and proposed performance - products that barely comply to legal specifications will receive no subsidy while as the difference grows, so will the corresponding subsidy, until a maximum amount.

The results of the full model analysis can be found in *Table 3* and their graphical representations in *Figure 5*. The results for scenarios 1 and 2 are identical to the ones for the reduced model; α reaches vales of around 59% (1) and maximum values (2) respectively. This happens due to the fact that the additional structure compared to the reduced model does not affect the cost-benefit relationships between the costs of sustainability and non-sustainability, under the described conditions. This balance is slightly altered in scenario 3, where the non-compliance legislation pressure becomes active when the company, as best reaction, chooses to design a new product that does not comply to legal requirements regarding the specification. The value of NCL raises so that the additional cost of non-sustainability eliminates the previous benefit of not matching SL; therefore, the value of α reaches a slightly higher level as compared to the corresponding case of the reduced model.

Scenario 4 describes the result of an environmental incident on the final value of α. Even though the system has come to an equilibrium before the event, the equilibrium gets disturbed by an incident that causes a sudden increase in the public awareness. The increased public awareness is slowly converted to higher specifications legislation through the pressure, and finally alters the company's best response to levels of about 69%. A similar effect is caused by the scientific studies (scenario 5); new knowledge about the implications of human activities cause small increases in public awareness in forms of steps every time a new study gets public. Even though studies are released throughout the whole simulated period, their effect is visible only

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6a	Scenario 6b	Scenario 7	Scenario 8	Scenario 9
α	0.5875	1	0.2052	0.6872	0.6504	0.7439	0.7438	0.5875	0.5936	0.5935
W	0.5875	1	0.2052	0.6873	0.6504	0.7439	0.7438	0.5875	0.5936	0.5935
SL	0.5875	1	0.2052	0.6875	0.65	0.7438	0.7438	0.5875	0.5938	0.5938
NCL	4	4	4.875	4.125	4	4	4	4	4.125	4.125
p	30.83	60	19.1	37.48	35.02	23.13	23.13	25.83	26.24	26.24

Table 3. Simulation results for the reduced model

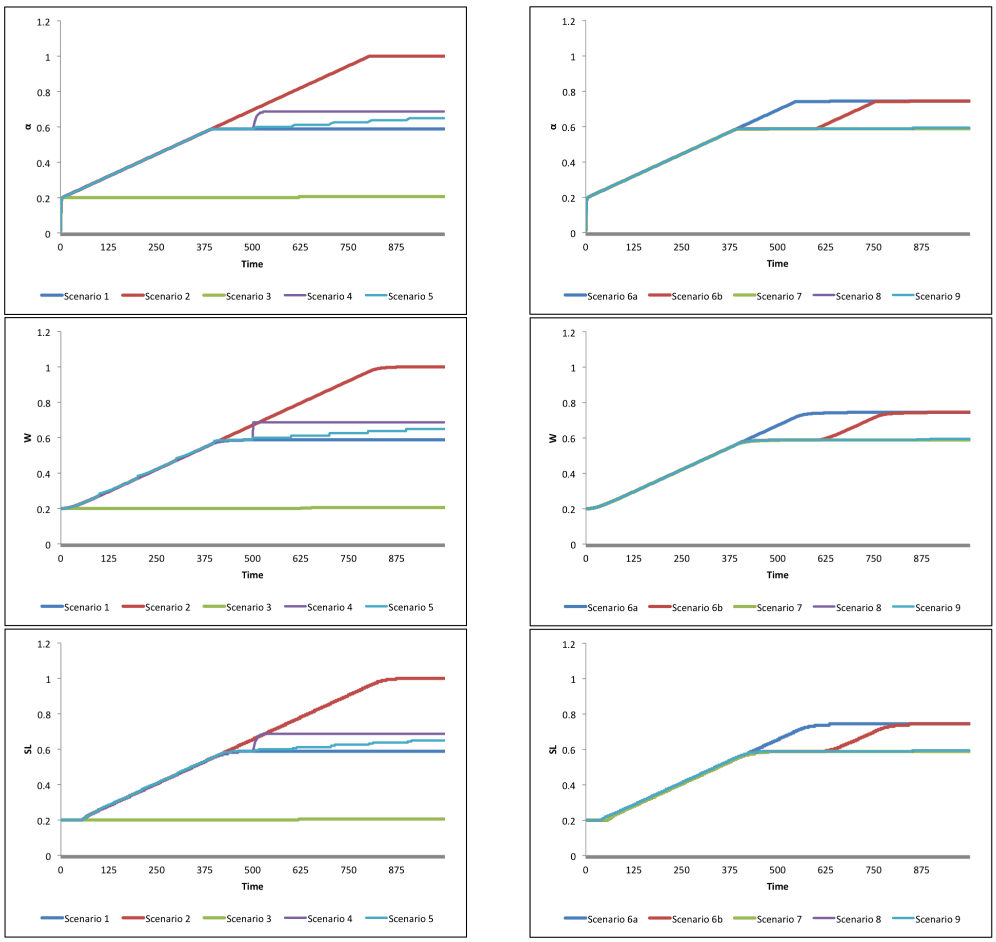


Figure 5. Results for Scenarios 1-9

in later stages, once the value of α has reached the levels of scenario 1, after which, the value follows the stepwise increase of the public awareness (with the corresponding delay). Extending the simulation horizon over the levels presented in the graph allows us to see that α keeps rising until its maximum possible value, provided that new research studies continue to become public.

Scenarios 6a and 6b corresponding to a technological shock are the ones that give the most important results: the value of α reaches 75%, much higher than the base case scenario, while at the same time the price of the product is the lowest (excluding scenario 3 that may be unrealistic), a combination that maximizes the market capture. It is interesting to see that no matter when the technology shock happens, the final results in both cases (a) and (b) are identical. Another important result is described in the outcome values of scenario 7, which are identical to the ones of the base case: this fact indicates that the original assumption of a uniform distribution regarding clients' ability to purchase the product and individual expectations regarding its performance is a very good approximation to reality, facilitating calculation in more complex scenarios.

On the contrary, the results of scenarios 8 and 9 indicate that either intervention by a social planner through educational efforts to reduce the thresholds of pressure for higher legislation or by means of subsidies, are questionable practices. The final levels of α at about 59.5% hardly justify the corresponding costs that need to be incurred by the social planner. In the aftermath of these results, we examine a slightly different case where education does not alter the existing (but rather difficult to define) thresholds, but the behavior of clients directly, affecting the shape of the S_{acc} function (Scenario 10). We assume that the social planner manages to shift the shape of S_{acc} to an increasing convex function, indicating a right-skewed distribution for customers' acceptance of product's sustainability performance. Indeed, this intervention proves to be much more efficient than the ones described in scenarios 8 and 9. The value of α reaches levels of about 66%, with similar values for W and SL.

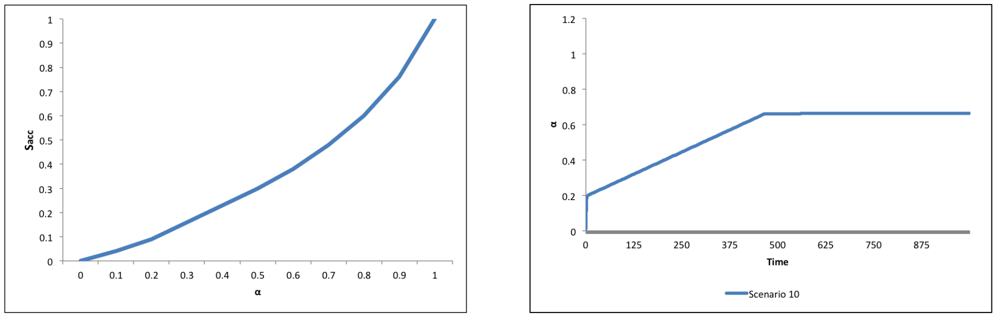


Figure 6. Relationships and results for Scenario 10

5 Summary and policy recommendations

Companies make products in order to gain financial benefit from their sales; a new product is expected to contribute to this cause - it needs to provide sufficient profit margin that will justify inversion in its production. Enhanced characteristics have to be accompanied by a cost-benefit analysis that demonstrates the benefit of incorporating them and may be proven to create competitive advantage. Even though these, mainly financial, tradeoffs are true for any product, sustainability awareness adds another important aspect: the needs of the society. Environmental and social conditions affect the importance of the tradeoffs described in the previous paragraphs and can mitigate or multiply the effect of each and every one of them, leading to new points of balance.

Products are designed to meet the requirements and expectations of potential customers. In order to do so, they have to incorporate characteristics and features that fulfill a series of external requirements set by users' expectations and existing regulation. Regulation determines minimum specifications for a variety of features based on scientific knowledge and is usually a result of discussions among scientific and industry experts, politicians and the local community. On the other hand, customers' expectations regarding a product's performance may vary substantially, depending on their previous individual experiences with similar competitors' products or other products from the same manufacturer.

The proposed approach captures the interaction between the design of a product and the expectations of the customers that are going to acquire it. The center focus of the dynamic hypothesis model is to understand how do customers desires and expectations affect the design of a new product and in turn, how does the design stimulate public awareness of the sustainability problem. By answering the questions of interest, we are able to better understand the interactions between the need for design for sustainability and a new product design. By identifying the underlying relationships, companies can be in a position to schedule the incorporation of advanced features that improve the sustainability performance of their products in a way that offers them competitive advantage, while minimizing the risk of over-performing in an sustainability-wise immature market.

We presented two versions of a model that captures the interaction between the need for sustainability and public awareness: a reduced and a full version of the model. The reduced version allows us to examine the best response to current market conditions, taking into account limitations like the available technology and legislation. A company can use this model in order to design the first version of a new product that will be released in the market in the immediate future. The full version allows to follow the developments in the market conditions and plan the design of the following versions of the new product as the best response to the corresponding conditions; a company can use the full model to plan its strategy.

We examined nine scenarios of possible current and future conditions. We first formed a base case scenario (1) that describes a simple market and serves as a basis of comparison, and depart from it in 9 cases that correspond to possible alternatives of the base case. The results of the analysis indicate that the most important factor is the reaction of the customers to the sustainability performance of the product and its price, represented in the model by the S_{acc} and p_{acc} functions respectively. Increasing the sustainability performance results in the product meeting the expectations of a greater number of potential customers, leading to the product reaching a higher percentage of the market pool. On the other hand, it also implies a more expensive product and, therefore, fewer potential customers can afford its price. The point of equilibrium depends on the relative importance of one against the other at any given point in time; when environmental degradation is obvious, the market is driven towards more sustainable products, while in times of economical difficulties, the opposite is realized.

External factors such as an environmental incident or scientific research can influence the behavior of prospective customers through increased pressure to increase legislation, that is slowly transformed into stricter specifications and non-compliance legislation. A severe environmental incident can give rise to a sudden pressure for higher specifications legislation that will aim to prevent similar incidents from occurring in the future, as well as increase the penalties associated with companies that do not comply with the existing legislation, making it increasingly more expensive to operate in such a manner. Similarly, scientific research on the outcomes of current living practices increase our understanding of our actions and offer a closer view of distant consequences, that are commonly heavily discounted as opposed to imminent ones. In either case, the customers become more prone to look for products that follow their own higher expectations, creating an attractive market pool for the company to operate in, and the offered products will incorporate the characteristics that allow penetration in the growing sustainability-conscious market share.

In addition, we discussed effective policies that could induce a permanent shift towards more sustainable operations (Ferguson, Schmidt and Souza, 2010); social planner interventions in the forms of lobbying to increase the pressure for stricter legislation and subsidies for improved performance seem to offer questionable results, as the final equilibrium point of the product's sustainability level is extremely close to that of the base case. However, they do influence the time the system reaches its final equilibrium, decreasing the total time needed; they can be used as means of quick wins, in order to achieve some early results. On the contrary, a technological breakthrough regarding the cost of sustainable technologies can lead to important improvements; the value of α is increased by 26.6%. It is therefore in the interest of both the company and the community that enough capital is devoted to R&D spending regarding production techniques and new materials, on the expense of marketing and advertising.

Another important intervention is the possibility of altering clients' acceptance of the sustainability performance of the product through education. A social planner can use educational programs in school and direct advertising so as to induce the public towards more sustainable practices, at the time of comparing products. History has shown that a similar effect can take place not by an intended intervention, but because of an environmental incident that may shift customers' behavior (i.e. a pollution caused by a company's operations). The dynamics of such an interaction are, however, unknown.

Because of its spherical approach, our analysis can be of interest to practitioners, researchers and policy makers. Future research can be focused on a further deepening on the interaction among physical disorder and sustainability practices. As extreme weather conditions are expected to become more frequent due to the results of global warming, the importance of such incidents may increase substantially. On the other hand, future research should also look into a possible deteriorating effect of oblivion; do customers forget the need for sustainability once a certain high performance is reached, by considering it given? Or in a similar manner, how do priorities shift during difficult times? The recent global economic crisis has resulted in a considerable decline in the sales of biological products, but an increase in the sales of fuel-efficient vehicles. It would be interesting to examine the driver of this behavior and its preservability over time.

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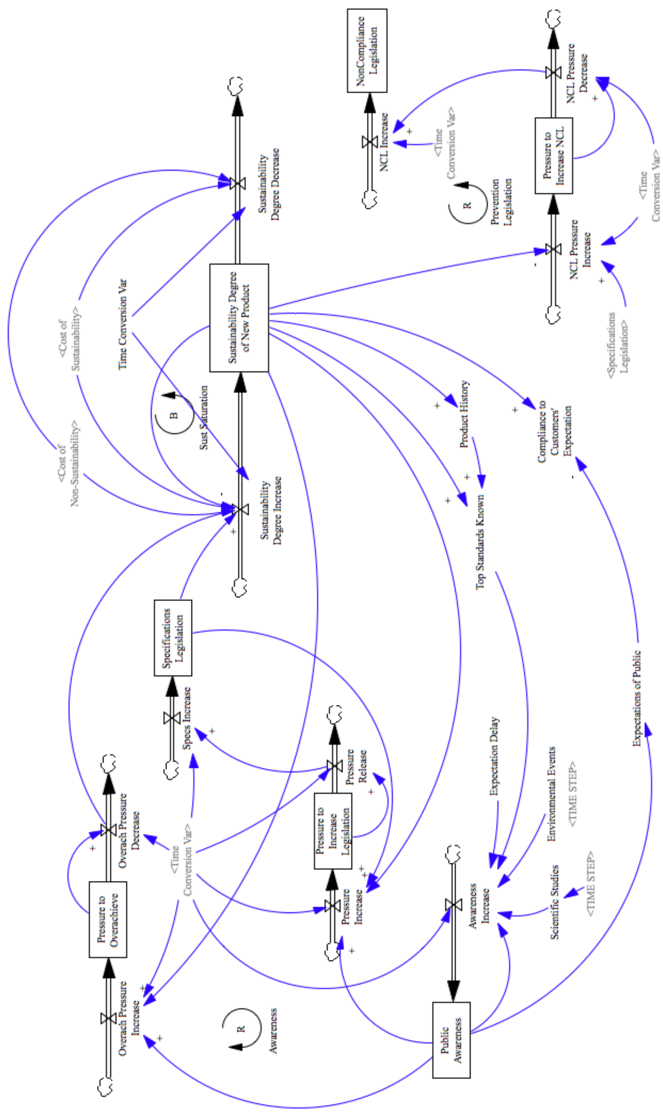
Appendix 1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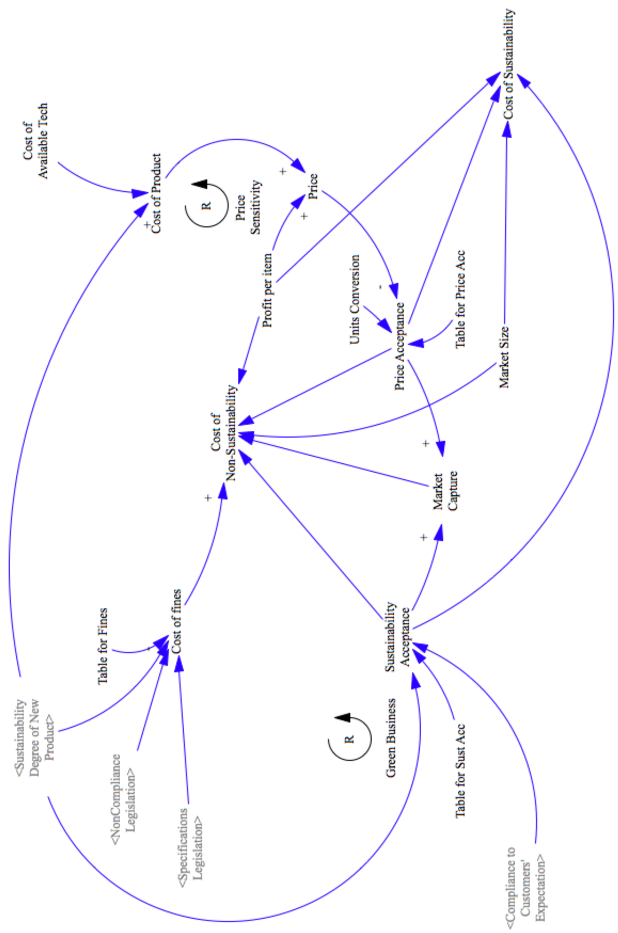
Appendix 2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