

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

**MEASURING PRODUCT SUSTAINABILITY:
A RISK-FOCUSED APPROACH**

by

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January, 2019

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MEASURING PRODUCT SUSTAINABILITY: A RISK-FOCUSED APPROACH

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of
Science in Industrial Engineering, Industrial Engineering Program**

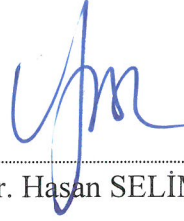
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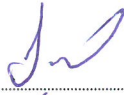
M.Sc THESIS EXAMINATION RESULT FORM

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Prof. Dr. Hasan SELİM for his continuous support, invaluable advice and understanding throughout my M.Sc. thesis. Thanks to his guidance, immense knowledge, and continuing motivation, I was able to overcome challenges.

I'm extremely grateful to general manager of the application company, Bülent KEŞLİ, and quality department team leader, Ayse ONAN.

I'm thankful to my parents, İbrahim SEZER, Necla SEZER, and my sister Ece SEZER GÜMÜŞ for their love and heartily support in my whole life.

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MEASURING PRODUCT SUSTAINABILITY: A RISK-FOCUSED APPROACH

ABSTRACT

Sustainability is the holistic approach that aims making future-oriented programming with economic, social and environmental dimensions. Sustainable product development is one of the most significant issues facing in today's companies due to rapid depletion of raw material resources, increase in the social and environmental impact of products, legislative regulations and awareness with regard to social and environmental issues. Within this framework, measuring product sustainability plays essential role in gaining and protecting competitive advantage. However, it is necessary to consider all risks associated with sustainability in order to measure the product sustainability effectively. In this regard, the objective of this study is to develop a risk-driven approach for measuring product sustainability. Previous studies in the related field are restricted due to the lack of dynamic and multidimensional measurement. However, as the decision-making environment is constantly changing in the real-world, a dynamic decision-making approach is needed. This study proposes an approach for measuring product sustainability that considers all of the related risks and risk interactions. To deal with the dynamic and multidimensional nature of product sustainability, the proposed approach employs system dynamics modeling. To confirm the applicability of the proposed approach a real-world application is presented.

Keywords: Product sustainability, system dynamics, risk management

ÜRÜN SÜRDÜRÜLEBİLİRLİĞİNİN ÖLÇÜLMESİ: RİSK ODAKLI BİR YAKLAŞIM

ÖZ

Sürdürülebilirlik, ekonomik, sosyal ve çevresel boyutlarıyla bugünden geleceğe uyumlu bir programlama yapılmasını amaçlayan bütünsel bir yaklaşımdır. Son yıllarda hammadde kaynaklarının hızla azalması, ürünlerin çevresel ve sosyal etkilerinin artması, yasal düzenlemeler, tüketicilerin çevresel ve sosyal konulara ilişkin bilincinin artması gibi nedenlerle sürdürülebilir ürün geliştirme günümüz firmaları açısından çok büyük bir öneme sahiptir. Bu kapsamda, ürün sürdürülebilirliğinin ölçülmesinin firmaların rekabet avantajı elde etmelerinde ve bu avantajı korumalarında önemli bir rolü vardır. Ancak, ürün sürdürülebilirliğinin etkili bir biçimde ölçülebilmesi için ilgili tüm riskleri bütünlük bir biçimde ele alan yaklaşımların kullanılması gerekmektedir. Bu gerçeklerden yola çıkılarak, bu çalışmada ürün sürdürülebilirliğinin ölçülmesine yönelik risk odaklı bir yaklaşım geliştirilmesi amaçlanmıştır. Bu alanda önceden yapılmış çalışmalar sürdürülebilirliğin çok boyutlu yapısını ele almamaktadır ve dinamiklikten yoksundur. Ancak, gerçek yaşamda karar çevresi sürekli değiştiğinden dinamik bir karar verme yaklaşımına gereksinim vardır. Bu çalışma, ürün sürdürülebilirliğinin ölçülmesi için ilgili tüm riskleri ve risk etkileşimlerini dikkate alan bir yaklaşım önermektedir. Bu yaklaşım, ürün sürdürülebilirliğinin çok boyutlu ve dinamik yapısını ele alabilmek için sistem dinamiği modellemesinden yararlanmaktadır. Önerilen yaklaşımın uygulanabilirliğini ortaya koymak amacıyla bir gerçek yaşam uygulaması sunulmuştur.

Anahtar kelimeler: Ürün sürdürülebilirliği, sistem dinamiği, risk yönetimi

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CHAPTER ONE

INTRODUCTION

Companies today give weight to the concept of sustainability to gain competitive advantage. Sustainability takes the effective utilization of natural resources and environmental effects as well as economic growth into consideration. In the long term, it keeps the organizations alive and gives them a competitive edge. Within this time course, companies have acquired a responsible point of view not only in financial, but also in environmental and social issues. As a result, companies aim to produce sustainable products by integrating the concept of sustainability into their production process. This concept, which is rapidly gaining importance these days, have brought about risks while it has created various opportunities to the companies. Only the businesses that restructure their production processes and reorganize their products by assessing the risks and taking measures against them are to gain a competitive advantage. For this reason, businesses are creating a new market demand by diversifying their products in order to produce more sustainable and greener products and thus are acquiring an advantage in competition.

Companies are setting various goals by reorganizing their methods of working to obtain significant and permanent improvements in environmental and social issues. These new policies aim to create a more sustainable value chain by working through zero waste management, using 100% renewable energy and selling environmentally friendly products through the effective utilization of resources.

Considering that it has reached almost 8 billion individuals in the year 2018, it is only possible to meet the needs of this rapidly growing world population by applying sustainable policies.

Researchers have come up with various methods to measure and evaluate the effect of sustainability on products. However, most of the methods presented do not adopt triple bottom line approach and do not evaluate environmental, social and economic aspects, which are the three major dimensions. Moreover, most of the presented methods have remained static, which renders them insufficient at analyzing behavior models of variables changing over time. Companies are able to make more

efficient decisions in the long term by means of these behavior models. Therefore, the aim of this study is, by considering the three main dimensions of sustainability, to analyze the interactions of variables over time in these three dimensions in measuring product sustainability. In order to achieve this, a system dynamics model was designed by using Stella Architect software.

This thesis consists of six chapters. The remainder of the thesis is organized as follows:

In chapter two, we initially give general information about sustainability, triple bottom line, product sustainability and product sustainability risks and we describe conceptual definitions about these topics.

In chapter three, we present system dynamics approach and implementation steps of system dynamics.

In chapter four, the literature review of sustainability, product sustainability, product sustainability risks and system dynamics is presented.

Chapter five includes our application. Firstly, we present general information about application company. We create system dynamics model in Stella Architect Software and two different scenarios were used to see the short term consequences of company's current decisions on sustainability and its three main dimensions.

Finally, chapter six includes concluding remarks and several ideas for possible future research.

CHAPTER TWO

PRODUCT SUSTAINABILITY

In this section, the concept of sustainability, the three major aspects of sustainability, and the basic concepts about the risks that establishments will have to face are presented.

2.1 Sustainability

18th century forestry is referred to as the birth of sustainability. However, the concept has been widely adopted and found applications in various industrial fields (Diaz-Dalteiro et al., 2016). That is the main reason why there have been many definitions provided for the concept of sustainability.

The first known definition for the concept of sustainability, according to the Report of the World Commission on Environment and Development, is stated as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. According to this definition, an accurate analysis of the needs of future generations and a responsible view in the consumption of resources are vital (The World Commission on Environment and Development, 1987).

Another definition by Munier (2005) states that “sustainability is a process involving people, institutions, natural resources, and the environment”. Corporate sustainability, as defined by Lo & Sheu (2007) is “a business approach that creates long-term shareholder value by embracing opportunities and managing risks from three dimensions: economic, environmental, and social dimensions.”

Winkler et al, (2010) argued that it is necessary to focus on the value chain as a whole in order to provide effective sustainable improvement.

The purpose of sustainability is to utilize the limited resources considering the needs of future generations. This can only be possible through companies’ research on sustainability. For instance, if a business conducts too much or unnecessary packaging in its manufacturing process, it causes product wastefulness, decreases

productivity and increases the costs of production, eventually hindering the environmental sustainability. In the long term, this will lead to a decrease in profit and social benefits. However, the same establishment is also able to lower environmental damages and cost of raw materials by organizing a sustainable production process which produces reusable products in suitable packaging. Thus, the firm proves to be considerate in the needs of future generations while using natural resources. This is the only way to obtain a sustainable improvement. Companies' effort to lower the pollution, which is actually the damage they cause to the environment, through research is another example. Businesses fulfill their responsibilities by lowering the damage to the environment and prevent workplace accidents by creating a healthier working environment. Thus, the companies not only make profits but also a reputation for themselves through their environmental-friendly approach.

Today, there exists regulations about sustainability to decrease harmful effects on environment. United Nations Framework on Climate Change and Kyoto Protocol are the examples for these regulations. Via this protocol, the focus is on curbing greenhouse gases which cause climate change by containing emissions.

Companies should implement decision making processes which integrate sustainability into their new product development cycles as well as their current products and processes. In this way, they will have considered not only economic benefit but also the environment and society with the measures they take.

Elkington (1997) brought about the concept of "sustainable business". He argued that profit making businesses should be considered along with their shareholders, society and environment as a whole. He also claimed that it is not right to limit sustainability in only environmental aspects, but that it also has social responsibilities. As a result, he stated that sustainability should be regarded as a framework that incorporates economic, environmental and social dimensions, similar to triple bottom line approach.

2.2 Triple Bottom Line Approach

There have been various approaches developed to assess sustainability. The most accepted among them is Triple Bottom Line (TBL) approach. In this approach, sustainability is taken into account in a framework that encompasses three different dimensions as economic, social and environmental factors (see Figure 2.1). As mentioned before, sustainability is an approach that accepts the finiteness of the resources and thus takes future generations into consideration while trying to meet the internal needs, and that aims to take multidimensional measures by considering not only economic benefits but also the social and environmental impacts of the products (Elkington, 1998). The economic aspect is regarded as crucial among production processes since the beginning of 20th century, and the most considered dimension in previous studies. The social aspect has become popular since 1970's and the environmental dimension has in recent years. The understanding of integrating these three dimensions with TBL approach has become common in the last few years. The World Commission on Environment and Development expressed that these three major dimensions should be integrated into their definition of sustainability in 1987. These three pillars of sustainability are stated as planet, profit and people in various studies (Sarkar et al., 2009). These dimensions have the same importance in measuring sustainability effectively.

When a company is making an assessment about sustainability, it should not only consider the economic dimension, but also should take the social impact of this assessment into consideration, and evaluate the effect on environment. This is the only possible way for a business to reach the ultimate goal in sustainability.

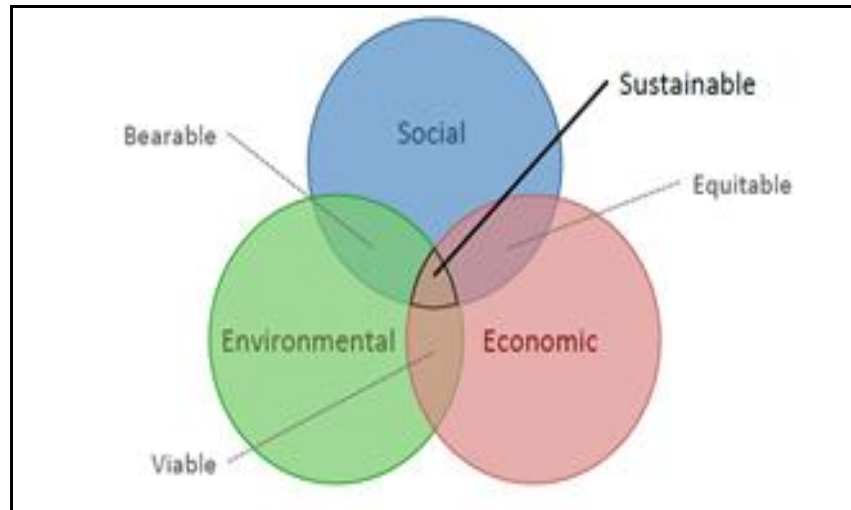


Figure 2.1 Three pillars of sustainability (Bruns, 2014)

As for the definition of sustainability, we need to utilize our natural resources efficiently and effectively by considering future generations while meeting the current needs. This dilemma lays a heavy burden on companies. They should look out for their employees, customers and shareholders along with their work's impact on ecology in addition to their profit seeking efforts (Madu & Kuei, 2012). This surely brings about challenges. The reason for this is that, as Elkington stated (1997), while these three main dimensions are related, they are also in constant conflict with each other. For example; as a business continues its production with working environment risks, only the responsibilities related to environmental dimension of the concept are visible at first sight. However, when the company face such a negative challenge, the employee turnover rates are the first process to be affected. As seen in this situation, these three dimensions should be considered in close relationship with each other and be evaluated systematically.

TBL is in a critical spot in manufacturing process management. Companies that apply TBL, which is a systems approach, both gain a competitive advantage and social benefits such as high customer satisfaction, correct use of human resources and fair working uptime, in addition to the environmental advantages like lower pollution levels, environmental accidents and also a lower energy consumption.

2.2.1 Economic Sustainability

In his “Pyramid of Corporate Social Responsibility”, Carroll (1991) argued that companies should adopt the three-dimensional approach to make economic progress.

When TBL approach is applied, we see that companies seem to gain no economic benefits in the short term and thus it is adopted often with difficulty by the firms. However, it is obvious that, not implementing this approach in that it has no short-term benefits, will leave the company with serious economic burden in case of an environmental or social problem. Therefore, the attitude of companies in this field should be proactive. It should not be forgotten that TBL approach will provide economic benefits in the long term (Madu & Kuei, 2012).

2.2.2 Environmental Sustainability

As mentioned in the definition of sustainability, current generations should act thoughtfully while consuming resources and consider future generations. Businesses should adopt approaches that minimize detrimental processes through their supply chain, that use environmentally friendly energy sources and develops production cycles manufacturing recyclable products, and which lowers waste and pollution. Emphasizing environmental aspect of production process does not necessarily mean that the economic dimension is ignored. Adopting both an environmentally conservative approach and gaining economic advantage is possible through the application of TBL (Madu & Kuei, 2012).

2.2.3 Social Sustainability

TBL approach emphasizes that while seeking economic benefits, social and environmental benefits should be considered as well. Large corporations in the world that have adopted this approach are building their reputation and indirectly acquiring economic benefits. Moreover, they aim to achieve higher employee loyalty through fair work distribution, acceptable working hours, integration of shareholders into the production process, better working conditions and consideration of individual skills of employees.

Sustainability is possible through the application of TBL which treats it in a holistic and systematic view.

2.3 Product Sustainability

Today, as industry and technology develop and the population increases, resources are gradually depleting. As a consequence, it should be kept in mind that the future generations will have to benefit from these resources as the current generations make use of them. The notion of sustainable systems and sustainable products were created based on this assumption.

Companies create values for shareholders like their customers, employees, investors and the society by manufacturing sustainable products. The establishments which are able to produce sustainable products gain customer satisfaction by producing environmentally friendly products and create a positive effect on its employees and the society through the social changes they have accomplished, in addition to acquiring economic advantages. It is necessary for both production and service sectors to utilize natural resources effectively, to reduce the waste, to develop regulations on environment and employees and to create customer satisfaction. Businesses are trying to produce more sustainable products by developing and reorganizing their production processes. Products that have the minimum negative impact on the environment are regarded as sustainable products.

Sustainable products are defined as those products that provide environmental, societal and economic benefits while protecting public health, welfare and environment over their full commercial cycle, from the extraction of raw-materials to final disposition (Zhang et al., 2012).

Dinh et al. (2009) defines a sustainable product as a concept that reduces resource consumption and minimizes waste down to acceptable levels, creates customer satisfaction by meeting the needs in time and which provides companies with profits along with these.

A sustainable product intends to minimize environmental impacts and provides the highest possible customer satisfaction. Sustainable products allow companies

gain a competitive advantage in the market. It also brings along other advantages like on time delivery, lower raw material costs, betterment of occupational health and safety, provision of high demand and customer satisfaction, less restraining regulations since the products are manufactured according to the environmental laws and regulations.

Increase in the production, the depletion of resources and negative effects on the environment have led the companies to produce sustainable products. Sustainable society is only possible through sustainable products. Most importantly, there is a necessity of various methods to evaluate and measure the sustainability of products. In product sustainability, TBL approach, which is one of these methods, can be applied to each phase in a product's life cycle.

As a result of the encouragement of producing sustainable products and the demand of sustainable products by shareholders, businesses have started to integrate sustainability in their production cycles (Bevilacqua et al., 2007). When customer satisfaction is considered, it is clear that sustainable products will not only provide companies with environmental benefits but also return profits in short term (Maxwell & van der Vorst, 2003).

Sustainability, via TBL approach, is adopted as a popular approach thanks to its benefits in environmental dimension like reducing waste and in that it considers production and design phases at the same time.

The increase in the value given by customers to the conservation of the environment and thus preferring sustainable products have led to the adoption of TBL approach. In order to be successful in this approach, it is necessary to reshape the phases in product's life cycle and to adopt eco-design approach. In Eco-design, or Design for Environment approach, while the environmental aspect is considered, the social and health approaches are continually conserved (Fiksel, 1998). Many components such as environmental risk management, product reliability, waste management and conservation of resources are taken into account while a multi-factorial approach is being organized. This is a more extensive approach compared to the classical product life cycle and has numerous components from the supply chain

to the utilization of resources and waste management; from raw material management to the reduction of energy usage in factories. As a consequence of considering many components, companies that adopt this approach have a lower cost and a higher competitive presence.

In design for environment approach, the environmental impact of products and waste management are kept in mind, and the total life cycle is taken into consideration from the beginning of the manufacturing to the delivery to the end consumer. As a result, businesses do not only produce, but also become aware of the impact their product inflicts on the environment. This holistic point of view allows us to become aware of the burden which the product leaves on the environment, to supervise it and to minimize the impact (Wenzel et al. 1997).

As it is commonly accepted and as Fiksel and colleagues (1998) stated, while a classical TBL approach could be adopted environmentally, economically and socially, other studies have proven that there might be some other parameters needed to be considered in product life cycles. It was argued that there could be many factors that affect the product, production phases and the system. From this point forth; the system which is to be adopted by the companies must cover the product life cycle in a wide framework while it contains each factor of TBL.

2.4. Product Sustainability Risks

Risk is the presence of a possibility which can prevent any of an establishment's strategic, financial and operational goals from realizing. Within a production cycle of a product, there are both environmental and productive risks. Environmental risks should be investigated from the point of sustainability, and this is possible through risk management approaches only.

As TBL approach argues in the context of sustainability risks; environmental, social and economic risks and the interactions between these risks are determined. For instance; while a late delivery, which results in customer complaints, causes a loss of reputation for the company, an increase in such complaints will create a non-value adding cost, and leading to a risk of a higher cost in production.

In studies about sustainability, it is necessary to predict and categorize the environmental impact of the product life cycle and future risks. Different approaches are being implemented for the study on long term effects of environmental risks in the life cycle of the product on the cost and the life cycle of the product. It is reported that while life cycle assessment can be implemented for the management of environmental risks and activity based-life cycle costing approach for the risks about the cost, there is a need for a system which provides the integration and a clear explanation of how these two interact with each other to obtain an actually sustainable product life cycle.

Risk management approaches are useful in providing the creation of more sustainable systems. As a matter of fact, risk management approaches of firms are foreseen to be about sustainability in the near future.

Companies are struggling to create their own sustainability programs. A risk management system which is handy in sustainability has to be a system which can be effectively applied and fulfill its legal responsibilities. This system should be in a way that it can consider its suppliers, workers, customers and shareholders, also the social and environmental impacts.

As for the literature, it is seen that there are many different types of risks defined in the sustainable risk management plans:

1. *Physical risks*: They represent physical risks such as climate change, droughts, floods and storms, which may directly affect each phase of production.
2. *Legal risks*: These express the legal measures which establishments should take for the risks companies may face. In the absence of these measures, side effects such as increase in cost and disruption in sustainability are likely to emerge along with legal responsibilities.
3. *Competitive risks*: Companies which lack necessary measures or fall behind their competitors in taking these measures in sustainability, will eventually lag behind other firms in the long term.

4. *Risks related to the reputation:* Being irresponsible to the climate change and sustainability may cause companies to fall behind in competition in the long term. In this respect, it is unavoidable for companies to lose reputation due to the irresponsibility in these matters (Mikes, 2007).

Considering all these, it is possible to argue that sustainability risk management has a gradually increasing importance and is a significant step of Enterprise Risk Management (ERM) approach. ERM is a system that enables the company to determine the critical risks that hinders the strategic goals and to realize risk management. In this system, however, risks related to reputation, competitiveness, environment and society are not expressed in detail. Risk management approaches that express the sustainability and the interactions between these dimensions are currently being developed. Hence, new approaches such as enterprise sustainability risk management and sustainable supply chain management are being tested.

In obtaining sustainability in an establishment, the three major dimensions which are substantial in TBL - economic, environmental and social - should be integrated to risk approaches. It is possible to realize this by dealing with four challenges:

- Taking measures to increase ecological activity,
- Taking measures to increase social activity,
- Increasing economic activity, while taking social and ecological impacts into consideration in decision making,
- Integration: Unifying other 3 dimensions.

In order to achieve this integration, there are different risk management approaches applied. In these approaches, various methods such as SSCM, ESRM, multi-criteria decision-making techniques and simulation tools could be used.

In this study, among system simulation tools, system dynamics modelling was used to analyze the risks, dynamic relations between the risks, and also the effects of

the decisions that the company will make in the future on the establishment were investigated through scenario analysis.



CHAPTER THREE

SYSTEM DYNAMICS APPROACH

System approaches and system dynamics we use today have developed since the beginning of 1900's. Systems thinking, which descend from the history of science, has become a conspicuous theory in the 20th century.

Systems thinking is often a framework in which a group of objects, working in step with each other to produce the same results, can be analyzed and defined.

Systems thinking can also be used as a decision support system. To exemplify, decision support systems in organizations can be used as integrated systems which enable rapid access to data and decision models to catalyze the decisions of executives in various issues (Çelik et al., 2011).

Problem solving necessitates that the system integrity and the analysis of the components that create the problem should be investigated within the unity of the system.

System is defined as the gestalt of many components interacting with each other to realize the same purpose.

Systems have a couple of features as presented in the following.

- They are classified into two groups as open and closed. Open systems are the ones that constantly interact with their environments, and which are open to development and change.
- Closed system are those that ignore the environment and the interaction with it.
- All systems have a framework but are separated from the environment by means of a border.
- A system consists of subsystems that constitute it and the components of these subsystems are compatible with each other.

- A system may tend to halt if the balance is threatened due to various reasons. This situation is referred to as entropy. Closed systems may cease to operate in such a circumstance since they are self-contained and self-maintaining, while open systems rebalance themselves with feedback mechanisms in case of this scenario.
- While variables are defined as the internal factors that influence the operation of the systems, the factors which are outside the system and yet affect the operation are called parameters.
- While in equifinality, which is an attribute of open systems, the same purpose can be achieved by inputs from different starting points with various cycles, closed systems have only one direction leading to the goal.
- Another attribute of systems is mutual dependence. The components forming a system have a mutually dependent relationship among themselves.
- Systems must be considered in a holistic approach.
- All systems have a specific purpose and each activity should be aimed at that particular goal in a particular order.
- The final feature of systems is synergy, where the effect of a whole system is larger than the simple sum of the effects of its components.

Negative and Positive Feedback Loops

Systems are comprised of interacting components which operate in coordination to reach their goal. The components that form a system require communication to achieve interaction. This is realized by a feedback mechanism. Therefore, a system reaches a position where it can operate in accordance with its surroundings. Through feedback, organizations reorganize the inputs they acquire from the environment at the end of a transformation cycle and feed it back to the system as data. In this manner, a feedback loop is not only able to reinforce the system but also stabilize it. The reason for this is that feedback acts both as a positive (reinforcing) and a negative (balancing) factor. The structure of a system is explained through feedback

loops. Causal feedback loop is the graphic illustration of a system. Feedback loops lead to a secondary effect in the system as they are affected by another variable in the system. While positive feedback has a reinforcing effect, the negatives have a balancing effect on the variables of the system (Walker & Salt, 2006). The details for these two feedback loops are presented in the following.

Positive Feedback Loops

This is the type of feedback that reinforces the system through causing more deviation strengthening the deviation in the same direction. Each positive effect in the system deviation gradually increases. In positive feedback, each plus creates another plus, similarly every minus forms another minus. The cycle cascades continually in a similar way. To illustrate; as birth rate increases, so does the population of the area, and the increasing population causes a higher birth rate. As seen in this example; the cycle continues to influence the variables positively (see Figure 3.1)

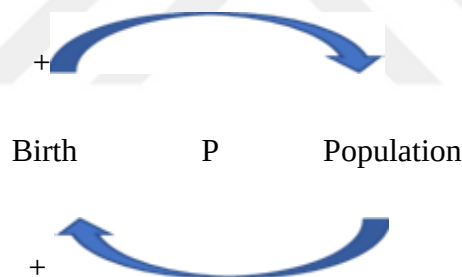


Figure 3.1 Positive feedback loop

Negative Feedback Loops

When a deviation from the target is detected in a system, the system attempts to balance itself to be able to reach the target again. This is done through negative feedback. In negative feedback, the loop recalibrates the system by comparing the desired performance and the deviation from it. To exemplify; if the price of a product increases, the number of consumers that want to buy it tends to decrease and so does the demand. The decrease in sales leads to a fall in the demand and causes an

increase in the price. Thus, the system tries to settle to an equilibrium (see Figure 3.2).

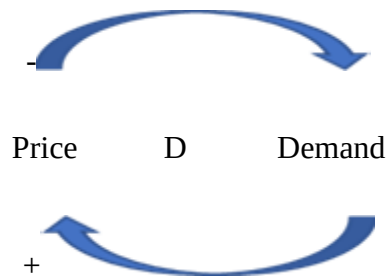


Figure 3.2 Negative feedback loop

System dynamics is defined as a process of creating a model that represents a real system by explaining the relations between the structure of the system, its variables and parameters for the problem at hand. This approach aims to analyze the structure of systems that we come across in real life, to create a model of it by defining the relations between variables of the system via feedback loops and eventually to improve the operation of the system.

System dynamics was initially defined by Jay Forrester in 1950's as "industrial dynamics". Forrester explained system dynamics as "a way of studying the behavior of industrial systems to show how policies, decisions, structure, and delays are interrelated to influence growth and stability". This approach has been used as a method to solve major socio-economic problems. Afterwards, the approach of "Limits to growth" by Meadows et al was suggested in 1972, aiming to deal with complex socio-ecological problems. "Limits to growth" approach is still being commonly used in sustainability measures (Turner, 2012). Although at first, system dynamics emerged as a system theory, it has found a wide field of use in time. Via system dynamics approach, the structure of complex systems is better explained and forms an effective support system for decision makers. The structure of the system is analyzed by expressing the interrelations of all the variables in the system through feedback loops. It clears the way for decision makers by informing about the possible situations in the future in changing decision-making environments with policy and scenario analysis. Forrester (1961) states the advantages of System Dynamics approach as follows;

- Better analysis of the behavior of constantly changing variables in the system,
- Providing explanations for companies about the interrelated aspects,
- Providing companies with precautions for future impact of their decision-making process by presenting these effects beforehand.

System dynamics models are used to study the structure of systems. In order to understand the structure of systems, modelling the operations is crucial.

System dynamics are expressed by using stock and flow variables. The changes occurring in the variables are accumulated in the system and this data influences future decisions. Interrelations of variables in system dynamics are defined as feedback loops.

Figure 3.3 illustrates the steps for system dynamics modelling process. In the first step, the problem at hand is determined. Structure of the system is designed through creating the feedback loops and the variables related to the problem. In the second step, a causal loop diagram illustrating the defined variables and feedback loops is formed. Interacting variables are determined and how they influence each other is investigated. These relationships are systematically illustrated via a diagram. In the third step, a system dynamics simulation model is created by giving values to the variables. The system is operated to observe the behavior of the variables in time. In the fourth step, the system structure is tested. In this phase, the model is improved through alternative scenarios. Accuracy of the model is tested in the fifth step. The sixth step is where the model is applied. An applicable simulation system that represents a real system is thus created (Forrester, 1994).

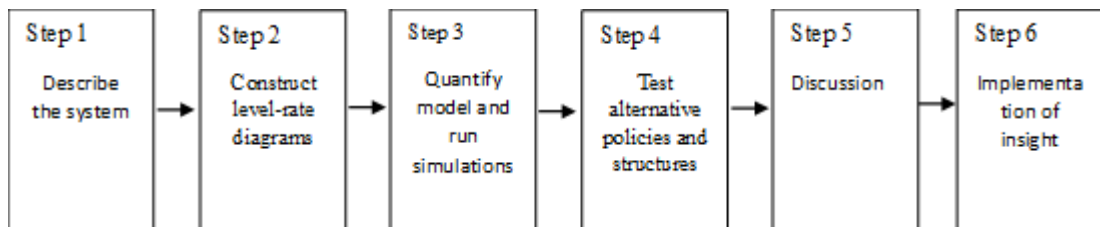


Figure 3.3 System dynamics process (Forrester, 1994)

As widely known, simulation models do not provide an optimal solution directly. In order to come up with an optimal solution, some alternative solutions are found and processed in the model to choose an appropriate one among various outputs.

It can be stated that system dynamics approach can be employed as an effective tool to the aim of sustainability.

Größler & Strohhecker (2012) implied that system dynamics approach is suitable for sustainability studies and can be applied to many issues in sustainability. System dynamics display the structure of the system by addressing issues such as feedback, stock and delay, and enables the analysis of the system through simulation.

Matters of sustainability also have a dynamic process due to changing environmental conditions. It is needed to establish a structural model that can adapt to the changing conditions. Therefore, it can be modelled through system dynamics approach. Companies also want to constitute a decision-making mechanism by structuring their decision-making process according to changing environmental circumstances to adapt to these circumstances as a whole. Companies resolve how they could better tackle the issues they encounter by determining the future policies in case of a different situation through the use of simulation tools like system dynamics. By analyzing scenarios about possible issues after building a system dynamics model, the companies have the option to take necessary precautions against them in a proactive approach or decide to adopt that particular policy or not by means of prepared analysis. Companies also make use of simulation tools when they are forced to make decisions on contradictory issues. Via system dynamics simulation modelling tools, it is possible to effectively realize decision making in a real-world environment. System dynamics models are implemented for decision making in tactical and operational levels, and additionally management strategies are tested through these models. Companies gain a competitive advantage by making strategic decisions while observing all possible relations through feedback loops in their decision-making process. System dynamics models have a deterministic structure.

In the analysis of nonlinear complex systems and scientific decision-making processes, effective methods and approaches are needed. System dynamics approach, which is one of these methods, is the process of effectively understanding and managing the interrelations of system and its components. As system dynamics approaches could be applied to every social system, it may also be integrated to the decision-making process in establishments. A dynamic structure is formed when a variable A influences variable B, and as a result of a cause-effect relationship, variable B provides feedback for variable A. Dynamic relations inside the structure of the system are expressed by a system dynamics model. By stating all feedback mechanisms inside the system through cause and effect relationship, it is possible to predict how the system behavior change in time. It is a useful method to understand the behavior of complex systems in time.

Risk management is a difficult process due to the complex and dynamic structure of the risks. In risk assessment process, the use static evaluation models lead to an ineffective assessment of the process. Dynamic structure of the risks can be illustrated through the use of system dynamics approach, which is one of the methods used to observe and analyze risks' change in time. The difference of system dynamics, as opposed to other approaches, in the analysis of the structure of complex systems is the usage of feedback, stock and flow which make it possible analyze the structure effectively (Liu & Zeng, 2017).

The interrelations of the three major dimensions of sustainability can be seen through systems thinking approach. It is possible to assess the interaction between the dimensions of the system using various scenarios. For example; in our model, as the quality level taking place in the economic dimension of sustainability increase, customer complaints decrease, and this leads to a higher reputation for the company. As seen here, a change in the economic dimension influences the social aspect of sustainability. Another example is that an increase in the environmental accidents, which is classified in the environmental dimension, increases the risk level in working environment. This boosts the employee turnover rate. Here we see the impact of environmental dimension on the social.

Similar to all other modelling approaches, system dynamics models are used to help better understand and have a better decision-making process (Elsawah et al., 2017). Taking all these into account, in this study, a system dynamics model is developed to measure product sustainability by considering all the risks and their interrelations.



CHAPTER FOUR

LITERATURE REVIEW

In this chapter, various studies about sustainability, product sustainability and system dynamics are presented.

Studies on sustainability have increased in recent years, proving that companies should also consider the environment in their development phases.

Fiksel et al. (1998) provided a framework to measure the sustainability performance for the first time in their study. They stated that companies intending to survive for long periods of time aim at producing sustainable products and that the three dimensions of sustainability should be considered as a whole to achieve this. They emphasized the importance of determining the key indicators and designated 15 key indicators that associate the three major dimensions of sustainability.

Sarkar et al. (2009) discussed three dimensions to evaluate product sustainability. They suggested various measurement methods to analyze product sustainability during design stage. They have considered the need to analyze social and economic methods along with the environmental dimension and applied a sustainable measurement method by integrating the other two dimensions to Life Cycle Assessment method. In their studies, they also analyzed the impacts of three different bottles on these three dimensions. They classified these bottles into three groups as disposable bottles produced for recycling, reusable metal bottles and plastic re-packaging bottles. They studied the effects of these bottles in social, economic and environmental dimensions.

Ghadimi et al. (2012) presented an extensive review that contains an evaluation of product sustainability. In the studies included in this field between 1987 and 2012, they remarked that there are two different assessment approaches as product and process. They categorized the methods used in the evaluation of product and process sustainability. These approaches are presented as; weighted fuzzy assessment methodology, product sustainability index, AHP with fluctuant weight analysis,

sustainable process index, modular-based sustainability assessment and Green Pro. They discussed the advantages and weaknesses of these approaches.

Zhang et al. (2012) suggested the use of Product Sustainability Index (ProdSI), which is a new 5-phase quantitative approach, and presented a quantitative example. Their evaluation method consists of the normalization, weighting and clustering steps. Clustering was implemented to three dimensions of sustainability. For economic dimension, direct and indirect cost, for environmental dimension, material usage and productivity, also for social dimension, safety and health were designated as indicators.

Shuaib et al. (2014) suggested Product Sustainability Index (ProdSI) and Product Sustainability Assessment (PSA) for product sustainability measurement. They argued that it is necessary to provide a sustainability evaluation for the whole life cycle of product with these approaches. They expressed this assumption via a quantitative example. For the economic dimension, initial investment, direct and indirect cost, profit and losses were taken into account. For the environmental dimension, material and energy usage, productivity, use of other resources, waste and also emissions were considered. For the social aspect, product quality and durability, its functional performance, product safety and health and legal regulations were determined as indicators. Through normalization and weighting, the Product Sustainability Index was processed.

Feng & Mai (2015) assessed functionality, manufacturability and reusability dimensions in addition to three main dimensions of sustainability. They used fuzzy multi-criteria decision-making method in their study.

Many different methods have been used in measuring sustainability. (see Table 4.1):

Table 4.1 Summary of existing sustainability assessment methodologies (Ghadimi et al., 2012)

<i>Methodology</i>	<i>Sustainable elements</i>	<i>Boundary of analysis</i>	<i>Method of analysis</i>
Environmental Impact Assessment (EIA)	Environment	Cradle to grave	Quantitative and Qualitative

Table 4.1 continues

Sustainability Target Method (STM)	Environment, economic	Cradle to grave	Quantitative and Qualitative
Weighted fuzzy assessment methodology (WFAM)	Environment, economic and social	Cradle to gate	Quantitative and Qualitative
Sustainable process index (SPI)	Environment	Cradle to grave	Quantitative
Product Sustainability Index (PSI)	Environment, economic and social	Cradle to grave	Quantitative
Fuzzy method for sustainability evaluation	Environment, economic and social	Cradle to grave and Cradle to gate	Quantitative and Qualitative
AHP with fluctuant weight analysis	Environment and economic	Cradle to grave	Quantitative
Process design for sustainability (PDfS)	Environment, economic and social	Cradle to grave	Quantitative and Qualitative
Modular –based sustainability assessment and selection (m-SAS)	Environment, economic and social	Cradle to gate	Quantitative and Qualitative
Life Cycle Index (LINX)	Environment, economic and social	Cradle to gate	Quantitative
Green Pro	Environment and economic	Cradle to gate	Quantitative

1. Environmental Impact Assessment (EIA): In this approach, different criteria are used to understand the impact of production on the environment and the environment is the priority of constant protection. There exist many EIA methods, and most of them have been tried to become integrated with Life Cycle Assessment approach.
2. Sustainability Target Method (STM): The purpose of this method is to associate the economic value of the product with environmental factors. However, this method does not include the social aspect of triple bottom line approach.
3. Weighted fuzzy assessment method (WFAM): This method suggested by Ghadimi et al, (2012), and it evaluates according to their weighting to help manufacturers in producing sustainable products. The missing piece of cradle to grave approach might be that it only includes raw material and production phases. According to some authors, this might actually be considered as an

advantage in that it is a corrigible aspect. Moreover, the most important advantage of this is that it contains all three components of Triple Bottom Line.

4. Sustainable Process Index (SPI): Krotscheck and Narodoslawsky suggested this index in 1996. This system studies the energy consumption and environmental impacts in industrial processes. The advantage of this index is that it compasses the entirety of phases in production and the aftermath with its understanding of cradle to grave, while the disadvantage is that it only covers the environmental aspect of Triple Bottom Line approach.
5. Product Sustainability Index (PSI): Jawahir et al, put this approach forward in 2007. It is a successful system due to the fact that it includes all phases of both the product life cycle and all components of TBL. In this system, a standardized scoring system is used and all factors that could influence the sustainability of the product are considered.
6. Fuzzy method for sustainability evaluation: In this method, owing to cradle to grave understanding, both the steps of production and afterwards and all the components of triple bottom line are considered. Furthermore, the main advantage of the system is that it can successfully deal with non-conclusive data and that it can spontaneously produce qualitative and quantitative data (Hemdi, Mat Saman & Sharif, 2011).
7. AHP (analytic hierarchy process) with fluctuant weight analysis: According to the triple bottom line approach of product sustainability, this system which considers two dimensions -economic and environmental- was set forth by Qian et al (2007). This approach separates a system into different levels, and a different sustainability component for each level.
8. Methodology for process design for sustainability (PDfS): It consists of all three aspects of sustainability and can be applied to each dimension of production through its cradle to grave approach (Azapagic, Millington & Collett, 2006). As conclusion, by conducting a process design, the most

sustainable performance can be obtained in each production process according to this method.

9. A modular-based sustainability assessment and selection (m-SAS): Othman, Repke, Wozny & Huang put this system forward in 2010. While the three main components of sustainability are considered in production stage, different alternatives for process design are given and it makes it possible to choose between those alternatives.
10. Life cycle index (LInX): Khan, Sadiq & Veitch created this method which includes the advantages of life cycle assessment in 2004. In 2010, Bailey, Amyotte & Khan developed this method and made it possible to consider five main components which are the environment, health and safety (EHS), technology, cost and socio-political considerations. These five major factors are then separated into different parameters and thus a calculation system is obtained. The disadvantage of this system is that it cannot be applied to all steps through cradle to grave approach.
11. Green Pro: This method was presented by Khan, Natrajan & Revathi, in 2001. According to this approach, the main aim of process design is the minimum impact on the environment. The advantage of the method is that it tries to minimize environmental effects while considering economy and technology. For that matter, it is possible to develop an effective economic solution during the early stages of production cycle. Another advantage could be the possibility of its application to all steps in cradle to grave approach.

Studies related to the integration of sustainability to risk management and product sustainability have gained prominence in recent years. Various approaches have been adopted and numerous studies have been conducted about product sustainability.

Palousis et al. (2008) worked on social and environmental dimensions of sustainability risks which companies encounter. They studied risk impacts on quality, time and cost, using life cycle assessment and life cycle costing approach. They used

fuzzy logic to evaluate the probability and intensity of risks, and they employed Monte Carlo analysis for the assessment.

Yilmaz & Flouris (2009) presented a conceptual framework for sustainability risk management. It considers the combination of financial, environmental and social justice performance as triple bottom line. They stated that the triple bottom line value should be at maximum while risks encountered in environmental and social dimension are minimized.

Giannakis & Papadopoulos (2015) considered the sustainability risks encountered in supply chain in their study and intended to designate which risks are more important to devise effective sustainability strategies. They identified 30 different risks in the main dimension of sustainability. By determining the causes and effects of the risks hierarchically, they analyzed the interrelations of identified risks through Failure Mode and Effects Analysis. As conclusion of the analysis, they state which regulatory actions the firms should take against the risks that they come across along the supply chain.

Göçer et al. (2018) argued that the risks are interrelated and they should be considered in a holistic way through a dynamic process. They classified connections between risks in five different categories. They analyzed these relations via a questionnaire-based method. To evaluate the risks in these categories in a food production system, they prepared 41 semi-structured questions which they acquired from 32 company executives.

As mentioned above, numerous approaches have been used to measure sustainability although the structural complexity of the sustainability concept and the interrelations of social, environmental and economic dimensions necessitate a systematic multi-dimensional approach. However, only a limited number of researchers study this concept holistically through the concept of system approaches. In order to fill the gap, Williams et al. (2017), carried out a comprehensive literature review which encompasses systems thinking and the concept of sustainability. They perused 96 articles between 1990 and 2015. The number of studies related to this topic is limited while there has been a significant rise since 2000 (see Figure 4.1).

They concluded that studies which integrate these concepts in a multidisciplinary way have peaked after 2011. The basics of system approach which are causative cycle diagrams, feedback loops and structures which allow extensive analysis of a system's structure have been defined and related studies about various aspects of sustainability have been presented.

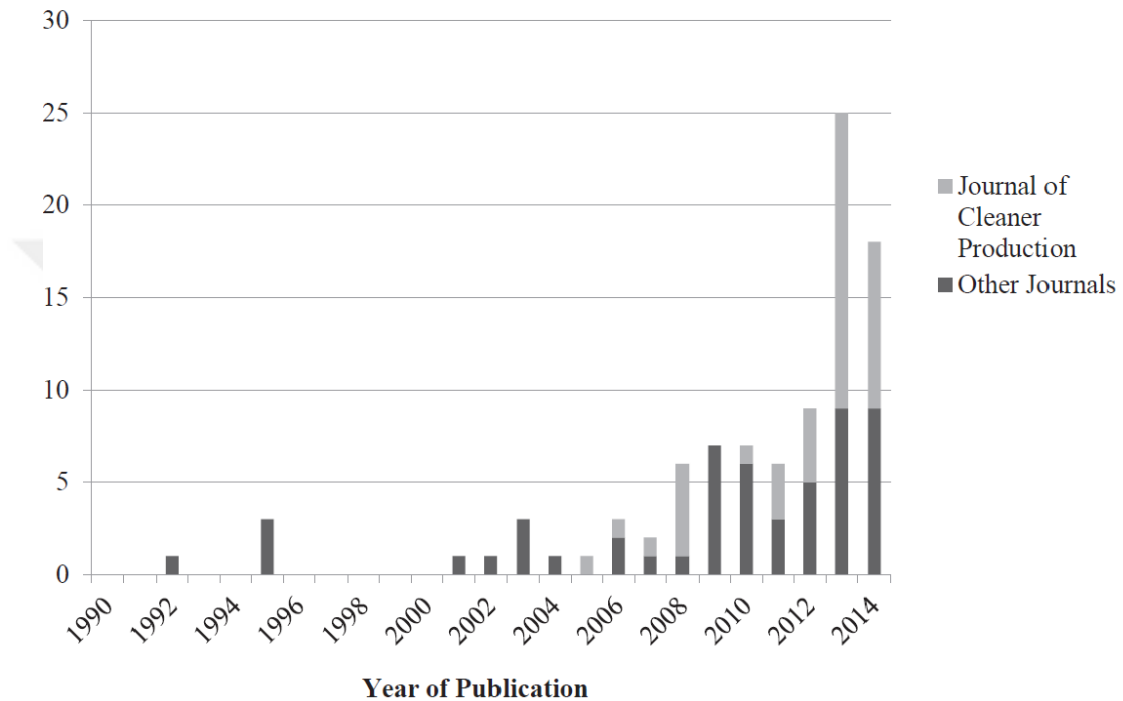


Figure 4.1 Distribution of publications on sustainability management from a systems-thinking perspective (per year).

Whiteman et al. (2013) utilized the systems notion to effectively define the dynamic relations between issues such as unemployment, social inequality and ecological topics.

The reviews related to sustainability concept are often based on traditional management theories. The fact that companies and socio-ecological structures are related is mostly ignored. However, the concept of sustainability is closely connected with firms and industry (Whiteman et al., 2013).

Through the use of feedback, system dynamics approach gives us a chance to study the relations between components holistically. Two important concepts in

systems thinking approach are the interrelations between components and feedback loops. It is crucial for executives to analyze related components in order to achieve sustainability. Determining the change in the behavior of components in complex systems provide opportunity to manage the challenges through decision making processes. Unless the outputs of feedback loops are analyzed accurately, a system's behavior cannot be predicted.

System dynamics approach, which can be applied to the solution of a range of problems, has also been used by other researchers in the management of risks in sustainability. The approach is also being used in the measurement of sustainability in this study.

Sterman (2001) defined a network containing feedback loops, problem cause and effect relationships in system dynamics approach. There are stocks and flows in this network. System dynamics model is a valuable tool thanks to its capability to display the change of stocks and flows through time. He emphasized the importance of feedback loops for executives. The decisions of executives cause changes in sociological and ecological aspects. These changes influence the future decisions of companies through feedback loops. Executives who fail to analyze feedback loops properly tend to experience difficulties in the system (Whiteman et al., 2013).

Lee et al. (2012) suggested the need for a multidimensional and dynamic structure in measuring sustainability. They argued that triple bottom line and system dynamics approach are needed to measure sustainability. They developed a system dynamic model on public bicycle system, and observed the behavior of five different components through time. They tried to improve the system through scenario analysis.

Lee et al. (2014) suggested a system dynamics model to check the vitals of patients remotely. In their model, they presented a causal loop diagram showing the dynamic relationship between users, hospital database, phones and devices which measure the vital signs. They made a variety of scenario analysis.

Marvuglia et al. (2015) presented a study emphasizing the need to create a system dynamics model.

Onat et al. (2016) developed a system dynamics model to analyze the impact of alternative vehicle technologies on sustainability. They composed a causal loop diagram to show the economic, social and environmental impacts on transportation system.

In an attempt to evaluate the sustainability of Brazilian ethanol production, Guevara et al. (2017) developed causal loop diagrams to exhibit the relationships in the system and proposed a system dynamics model by using flow and stock diagrams (Guevara, Silva, Hasegawa, & Venanzi, 2017).

Liu & Zeng (2017) developed a system dynamics model to evaluate the risks in renewable energy investment projects. They addressed three main risks in renewable energy investments which are technical, policy and market related risks. They created a causative relationship diagram and afterwards a system dynamics model to evaluate these risks and presented a quantitative example (Liu & Zeng, 2017).

Elsawah et al. (2017) contributed to the more effective conducting of system dynamics models and model design processes. They came up with five different case studies.

Hakim & Perdana (2017) proposed a supply chain management model by using a system dynamics model to increase the income of farmers producing potatoes. They created five different scenarios under the favor of this model and analyzed the impact of these scenarios on income growth of farmers.

Onat et al. (2017) made an extensive literature review in order to reveal the current difficulties and latest developments in LCSA applications. They stated that of the studies done in this respect, 40% covers the environmental aspect, while 9% is about the social dimension, and finally 3% studied the economic aspect. They argued the application of systems notion as a result of their study. Moreover, they explained the importance of systems notion and presented the applications containing system dynamics model.

Alamerew & Brissaud (2018) created a system dynamics model in product recovery management system to observe the interrelations of the three main dimensions which are economic, social and environmental aspects in addition to taking administrative and regulatory factors into account by using feedback loops. They developed a system dynamics model built on waste electrical and electronic equipment (Alamerew & Brissaud, 2018).

Yao et al. (2018) proposed a method integrated especially for waste cell phone management and recycling. Initially, the indicators were determined through life cycle assessment approach and then a system dynamics model was developed to analyze different scenarios. With the use of this model, determining the most suitable components which are the least hazardous for the environment and which enable the most effective use of resources was intended (Yao, Liu, Chen, Mahdi, & Ni, 2018).

Why should system dynamics be applied?

In the wake of literature research conducted, it was observed that traditional risk analysis methods were used in studies dealing with product sustainability. Traditional risk analysis methods often conduct qualitative evaluations, and they do not analyze the changing conditions dynamically. In addition, they do not exhibit the risks in the three main dimensions related to product sustainability and the interrelations between them dynamically. For instance, life cycle assessment is effective in analyzing environmental impacts. However, it does not consider economic or social effects. It is static and ignores the indirect effects taking place in the system. As a result, several methods have been suggested to obtain a more extensive evaluation which can take interrelations in three dimensions and to fulfill the need of such a method, and it is suggested to do research covering social and economic impacts in addition to the environmental effects. As a result, LCA appears as a new field of study, called life cycle sustainability assessment (LCSA). However, LCSA is proved ineffective in analyzing feedback mechanisms and interrelations between system components and requires systems notion applications. System dynamics models are able to deal with uncertainties in LCSA via scenario-based analysis in multi criteria decision making

processes. System dynamics model making use of cause-effect relationships is an effective method to make future decisions (Onat et al., 2017).



CHAPTER FIVE

APPLICATION

In this chapter, firstly, the information about the firm where the application was conducted is given. Then the steps of the study are elaborated upon, and the proposed system dynamics model is presented.

5.1 Company Profile

The company was established in 1945. It was renamed as a manufacturing and trading company in 1976. It was relocated to its modern facilities in Manisa Industrial Park in 1981. Its production range includes all types of suspension springs for light, medium and heavy commercial vehicles. It was recognized as a research and development center in 2010, and it has an innovative and inquisitive staff of more than 50 engineers and technicians. Being a global brand, the company accepts working through awareness of social responsibility in the entirety of its activities which is a fundamental aspect of its work ethics as a reflection of cherishing humbleness and respect for people and the environment. Each employee strives to fulfill their social responsibilities as individuals vested with this consciousness.

The Company's mission is to offer innovative design solutions to meet customers' demands for optimum performance, durability and efficiency in a wide range of commercial vehicle applications, to develop the most advanced design, production and management technologies in the sector, to create a reasonable work environment which is preferred by capable and successful employees, to maintain sustainable relationships with its employees, customers, suppliers and shareholders, by working for humanity, environment and nature.

Company's strategies are achieving the leadership in leaf spring industry, increasing design capabilities, providing customers with the best cost while maintaining the lowest weight possible, meeting quality expectations sustainably through more alternative solutions, and delivering products to customers all over the world on time.

5.2 Implementation Steps of the Proposed System Dynamics Model

Steps of system dynamics model application process for the purpose of measuring product sustainability are given below.

5.2.1 Description of the System

Due to ever-increasing legal regulations, customers' preference of environmentally friendly products, establishments' tendency to lower the amount of waste through recycling and the need to improve working conditions, companies place great emphasis on product sustainability to gain competitive advantage. It should be emphasized that while measuring product sustainability the risks should be evaluated extensively. The company, which we apply the proposed model at in this study, intends to measure the product sustainability effectively.

The product sustainability was measured by analyzing the risks which the company confronted. The risks under economic, environmental and social dimensions and their interrelations are considered. A system dynamics model is developed in this study in order to provide a decision support system to be utilized in foreseeing future circumstances and render effective decisions. By considering the environmental, social and economic dimensions, the risks affecting product sustainability and the indicators used in the analysis of these risks were identified. A total of 31 risks and indicators were designated, 16 of which are related to economic dimension, while 9 risks are related to social, and 6 risks are in the environmental aspect. Definitions of these risks and indicators about the three dimensions of sustainability are elaborated in Table 5.1.

Table 5.1 Definitions of sustainability risks and indicators

Sustainability Dimensions	Definition
<i>Environmental Dimension</i>	
Environmental accidents	all types of unintentional explosions, fires and hazardous material emissions which negatively affect environment or human health (Giannakis & Papadopoulos, 2015).

Table 5.1 continues

Product and energy waste	all types of used, unwanted or hazardous materials (Giannakis & Papadopoulos, 2015).
Compliance of governmental laws	defined as the corporate decisions being in accordance with the law in environmental aspect and employee health.
Pollution caused by organization	The results of any application which causes damage to the environment or harms any living thing in the nature during the production process.
Recycling	Returning of the materials, which could be used again, to the production cycle after undergoing various processes.
Working environment risk level effect	Any kind of risk level that employees face in their working environment during the production process.
<i>Social Dimension</i>	
Worker competency	Employees' fulfillment of their responsibilities and tasks in providing value.
Employee turnover ratio	An indicator of how long the employees will work in the company.
Stakeholder engagement	Considering the interests of all parties by including customers, shareholders and employees into all phases of production.
Human resources management performance	All efforts towards the purposes of the organization such as recruitment, administration and supervision of employees.
Physical load	A measurable representation of the resources spent on the accomplishment of any task.
Capability of human resources personnel	The role of human resources personnel in designating the right person for the right job.
Effective training hours per employee	Providing necessary and sufficient training for the employees about their functions in the company.
Company reputation	Positive and negative opinions of people about the company.
Information infrastructure	Structures supporting the information technologies used by the company.
<i>Economic Dimension</i>	
No-value added cost	Expenditure that adds to the total cost of a product but does not enhance its value from a consumer perspective.

Table 5.1 continues

Order fulfillment errors	Any errors occurring in the reception, transportation or delivery of an order.
Unit cost	Company's cost to build or create one unit of product.
Product obsolescence	When a product ceases to be useful and fail to meet the needs of the customers
Customers claims	The condition of dissatisfaction with a product by a customer
Flexibility	Amount of production which is regulated by the needs of customers
Quality level	Defined as the condition of being fit for purpose or use, meeting the needs of a customer in a timely manner and being conformant to the standards.
Efficiency	Achieving higher output in terms of volume and quality from the same input.
Level of innovation	The level of the company in creating a new product, idea or method.
Investment availability	Capability of a company to find suitable investment opportunities in topics such as production, innovation, information infrastructure and conformity with the law.
Production capacity	Volume of products that can be generated out of available resources.
Production cost	the total costs incurred by a business when manufacturing a product.
Late delivery	The situation when the delivery of a product does not meet the deadline.
Price	An amount of money paid for a product.
Profitability	Company's ratio of yielding profit (Lee et al., 2012).
Sales	The number of products company sells in a particular time period (Lee et al., 2012).

5.2.2 Construction of the Level-rate Diagram

To analyze the interrelations of risks, it is necessary to observe how the risks in the system influence each other by using positive and negative feedback loops after

defining the interrelations of the system's variables. Therefore, a causal loop diagram is needed. In Fig. 5.1, interrelationships of the variables are illustrated in a causal loop diagram.

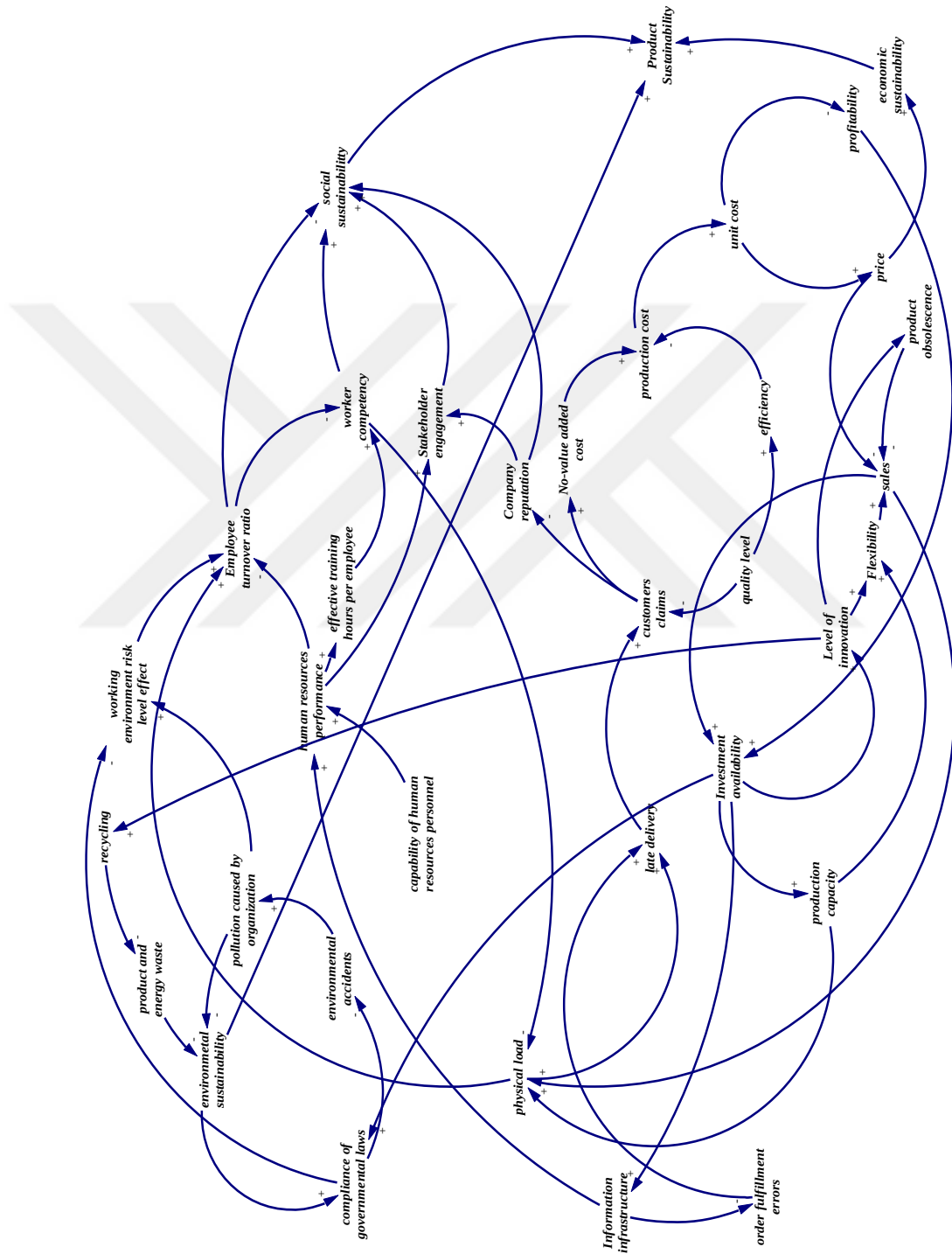


Figure 5.1 Causal loop diagram

The interrelationships of risks considered in the environmental dimension of sustainability are explained in the following. As the compliance of governmental laws increase, working environment risk level effect and environmental accidents decrease. Companies reduce their risks through improvements on occupational health and safety and environmental applications they put into action by conforming to legal regulations. The more a company invests in legal regulations, the more it complies with governmental laws. In addition, another variable with a positive feedback loop, environmental sustainability, has a positive effect on legal regulations. Environmental accident cause pollution, and pollution caused by an organization has a positive relationship with working environment risk level. As the pollution caused by an organization decrease, working environment risk level drops also. For example; pollution and disorder in the work environment leads to many risks in occupational health and safety. There is a negative relationship between pollution caused by organization and environmental sustainability. Sustainable products are designed to minimize the negative effects on environment. As the production of sustainable goods increase, environmental pollution decreases. Working environment risk level effect is also related to the laws. This type of risk, which is considered in environmental dimension, is also related to the employee turnover ratio in social dimension. As working environment risk level increases, employee turnover ratio also goes up. As employees do not want to work under unsuitable conditions, termination of employment and the number of inexperienced personnel increases.

It can also be stated that there is a positive relationship between recycling and level of innovation. As companies give more importance to new products, they can produce more sustainable products. Product and energy waste has a negative relationship with recycling. When a company increases its capacity to produce recyclable products, product and energy waste decreases. As product and energy waste decreases, environmental sustainability increases which results in a positive feedback loop by raising the level of compliance with the law. Improvements in environmental dimension contributes to the company's goal of producing sustainable products.

The risks in social dimension and the interrelationships between them are explained below in detail. If employee turnover ratio increases, physical load also increases. When the rate of employees leaving their company increases, the working competency of staff decreases. As human resources performance surges, the ratio of employees continuing to work with the company also rises. In addition, there is a positive relationship between working environmental risk which we consider in environmental dimension and employee turnover ratio. Considering all these relationships, it can be stated that as employee turnover rate is lowered, social sustainability mounts. As worker competency rises, employee workload goes down, and it results in an elevated level of social sustainability. Furthermore, worker competency and effective training hours per employee index scale up accordingly. When effective training is given, working competency of employees increases. An increase in the human resources management performance also leads to an increase in this index.

Improvements in information infrastructure and capability of human resources personnel augments human resources management performance. This increase leads to an upwards movement in stakeholder engagement, which is also related to company reputation. As a company gains reputation, confidence in that company is assured and stakeholders engagement increases. An advance in stakeholder engagement and company reputation also increases social sustainability. As customer claims decrease, company reputation rises.

Information infrastructure and physical load influence two main dimensions. Improving information infrastructure influences economic dimension by lowering order fulfillment errors. Companies augment their information infrastructure through investments. As a result, through positive and negative feedback loops, worker competency, stakeholder engagement, company reputation and employee turnover ratio influence the social dimension. As order fulfillment errors, which is one of the risks considered in economic dimension, rise up, deliveries experience delays. Moreover, an increase in workload in social dimension will also raise late deliveries. When late deliveries multiply, customer claims are to surge. As a result of customer

claims, which cause reputation loss, returned products rise in number and it increases no-value added cost.

If the company produces high quality products, the amount of customer claims decreases and it results in a higher level of productivity. The increase in no-value added cost and lower levels of productivity influences production cost both positively and negatively. As production costs rise, unit costs also surge. As unit cost rises, the price increases and results in a lower profitability. As the profitability and sales of the company mount, its capacity to invest increases accordingly. The company directs its investments towards increasing its production capacity, legal regulations and information infrastructure.

Flexibility is positively affected by the level of innovation. Advances in innovation decreases product obsolescence. As sales increase, the workload in social dimension goes up as well, however the sales continue to increase as the company manufactures innovative products that meet the needs of the customers. An increase in price causes sales to drop. The price, which is influenced by many factors as a result of feedback loops, affect sustainability in economic dimension. Through positive and negative feedback loops, the effects of interrelations of risks in three major dimensions on sustainability are shown in a causal loop diagram.

5.2.3 Quantification of the Model and Running the Simulations

Stock, flow and converters, whose interrelations were defined by using feedback loops, are explained and the equations and parameters which are designated for the quantification of the model are presented in this phase of the model. In order to simulate the model, causal loop diagram was quantified. Stella Architect software was used to create the system dynamics model. Stock, flow and converters were used in the model. Stocks explain the status of the system. Flows are utilized to display an action or activity. Flows are displayed as clouds, pipes, taps, flow adjuster and one-way or bidirectional arrows. Flow rate is calculated by a mathematical expression or numerical value written in flow adjuster. Converters transform inputs into outputs. Connectors are used to show the relationships and interactions in the system. A system dynamics model is designed in this study by utilizing these instruments. In

the model, the values received from the company were simulated between 0-1 (see Table 5.3).

The stocks considered in the model are specified as level of innovation, compliance of governmental laws, information infrastructure, production capacity, employee turnover and sales (see Fig. 5.2).

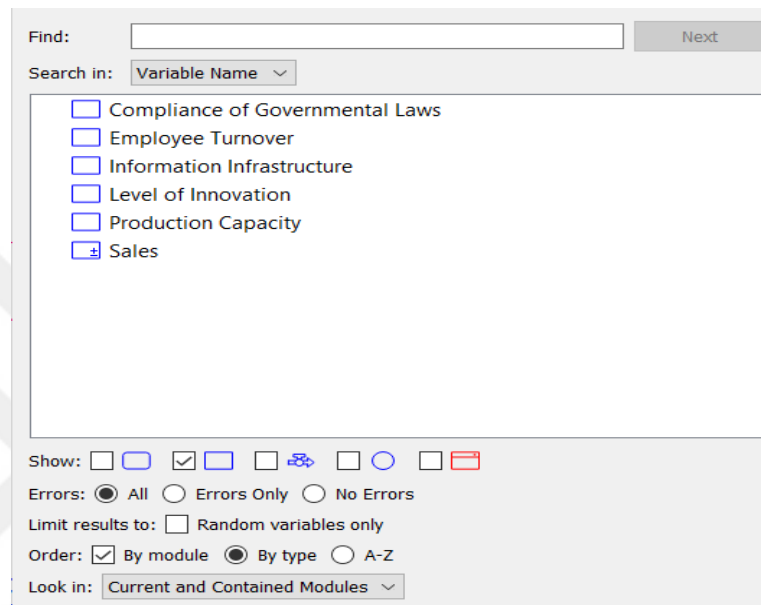


Figure 5.2 Stocks of the model

In the model, the flows are specified as capacity change, compliance of governmental laws change, employee turnover change, information infrastructure change, innovation change and sales change (see Fig. 5.3).

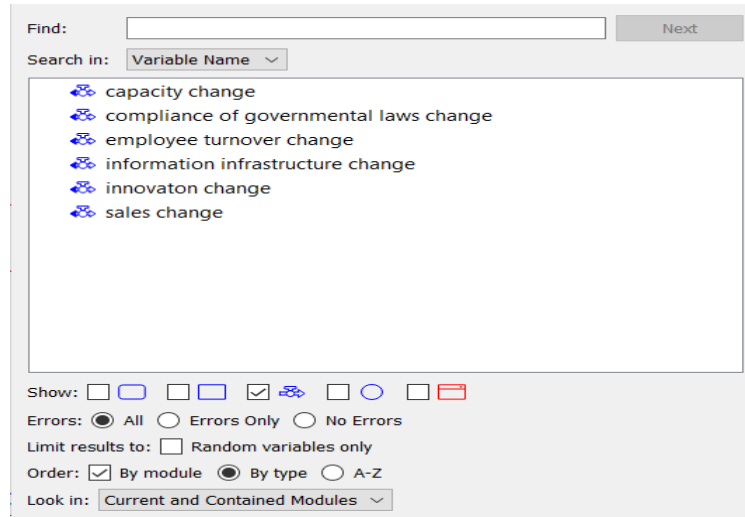


Figure 5.3 Flows of the model

Converters in the model are specified as; average sale, capability of human resource personnel, company reputation, compliance of governmental laws effect, compliance of governmental laws rate, compliance of governmental laws ratio, customers claims, desired profitability, economic dimensions, effective training hours per employee index, employee turnover normal, employee turnover target, environmental accidents, environmental sustainability, flexibility, HRM performance, information infrastructure rate, information infrastructure ratio, investment availability, late delivery, level of innovation rate, level of innovation ratio, max price, no-value added cost, order fulfillment errors, physical load, physical load effect on delivery, physical load effect on turnover, pollution caused by organization, price, price effect, product and energy waste, product obsolescence, product sustainability, production capacity rate, production capacity ratio, production cost, productivity, profitability quality level, recycling, sales target, social dimensions, stakeholder engagement, unit cost, worker competency and working environment risk level effect (see Figure 5.4).

Find: Next

Search in: Variable Name

- ☐ average sale
- ☐ capability of human resources personnel
- ☐ company reputation
- ☒ compliance of governmental laws effect
- ☐ compliance of governmental laws rate
- ☐ compliance of governmental laws ratio
- ☐ customers claims
- ☐ desired profitability
- ☐ economic sustainability
- ☒ effective training hours per employee
- ☒ efficiency
- ☐ employee turnover normal

Show: ☐ ☐ ☐ ☐ ☒ ☐ ☐ ☐

Errors: ☒ All ☐ Errors Only ☐ No Errors

Limit results to: ☐ Random variables only

Order: ☒ By module ☒ By type ☐ A-Z

Look in: Current and Contained Modules

Find: Next

Search in: Variable Name

- ☐ employee turnover target
- ☒ environmental accidents
- ☐ environmental sustainability
- ☒ flexibility
- ☐ HRM performance
- ☒ Information infrastructure rate
- ☐ Information infrastructure ratio
- ☐ investment availability
- ☐ Late delivery
- ☒ level of innovation rate
- ☐ level of innovation ratio
- ☐ max price

Show: ☐ ☐ ☐ ☐ ☒ ☐ ☐ ☐

Errors: ☒ All ☐ Errors Only ☐ No Errors

Limit results to: ☐ Random variables only

Order: ☒ By module ☒ By type ☐ A-Z

Look in: Current and Contained Modules

Figure 5.4 Converter of the model

production capacity rate

Show: ☐ ☐ ☐ ☐ ☒ ☐ ☐ ☐

Errors: ☒ All ☐ Errors Only ☐ No Errors

Limit results to: ☐ Random variables only

Order: ☒ By module ☒ By type ☐ A-Z

Look in:

Find:

Next

Find:

Next

Search in:

Variable Name

production capacity rate

production capacity ratio

production cost

profitability

quality level

recycling

sales target

social sustainability

stakeholder engagement

unit cost

worker competency

working environment risk level effect

Show:

Errors:

AllErrors OnlyNo Errors

Limit results to:

Random variables only

Order:

By moduleBy typeA-Z

Look in:

Current and Contained Modules

Two and more factors effect variables are shown by using equations. Equations within the model are presented in Table 5.2.

Table 5.2 Equations of the Model

		<i>Variables</i>	<i>Equations</i>
<i>Environmental Dimensions</i>	1	environmental accidents	compliance_of_governmental_laws
	2	product and energy waste	recycling
	3	compliance of governmental laws effect	investment_availability* compliance_of_governmental_laws_ratio
	4	compliance of governmental laws rate	compliance_of_governmental_laws_effect* environmental_sustainability
	5	compliance of governmental laws change	(1-compliance_of_governmental_laws)* compliance_of_governmental_laws_rate
	6	pollution caused by organization	environmental_accidents
	7	recycling	Level_of_Innovation
	8	working environment risk level effect	compliance_of_governmental_laws
	9	environmental sustainability	0,4 *(1-pollution_casued_by_organization) + 0,6 *(1- product_and_energy_waste)
<i>Social Dimensions</i>	10	employee turnover target	employee_turnover_normal* (1+"working_environ ment_risk_level_effect") * (1+physical_load_effect_on_turnover) * (1- HRM_performance)
	11	physical load effect on turnover	physical_load
	12	physical load	(Sales / Production_Capacity) * (1-worker_competency)
	13	worker competency	effective_training_hours_per_employee * (1 - Employee_Turnover)
	14	effective training hours per employee	HRM_performance
	15	HRM performance	capability_of_human_resources_personnel * Information_Infrastructure
	16	employee turnover change	(employee_turnover_target-Employee_Turnover) * Employee_Turnover/employee_turnover_target
	17	stakeholder engagement	company_reputation * HRM_performance

Economic Dimensions	Table 5.2 continues		
	18	company reputation	1 - customers_claims
	19	customers claims	(1-quality_level)*Late_delivery
	20	Information Infrastructure rate	investment_availability* Information_Infrastructure_ratio
	21	information Infrastructure change	(1-Information_Infrasturaction)* Information_Infrastructure_rate
	22	order fulfillment errors	Information_Infrastructure
	23	late delivery	order_fulfillment_errors* physical_load_effect_on_delivery
	24	physical load effect on delivery	physical_load
	25	social sustainability	stakeholder_engagement * company_reputation + (1-Employee_Turnover) * worker_competency
	26	quality level	Level_of_Innovation
	27	efficiency	quality_level
	28	no-value added cost	customers_claims
	29	production cost	no_value_added_cost/(1-efficiency)
	30	unit cost	production_cost
	31	price effect	price
	32	product obsolescence	Level_of_Innovation
	33	level of innovation rate	investment_availability*level_of_innovation_ratio
	34	innovation change	(1-Level_of_Innovation) * level_of_innovation_rate
	35	production capacity rate	investment_availability*production_capacity_ratio
	36	capacity change	(1-Production_Capacity)* production_capacity_rate

	Table 5.2 continues		
	37	flexibility	$0,47 * \text{Level_of_Innovation} + 0,53 * \text{Production_Capacity}$
	38	sales target	$\text{average_sale} * (1 + \text{price_effect}) * (1 + \text{flexibility}) * (1 - \text{product_obsolescence})$
	39	sales change	$(\text{sales_target} - \text{Sales}) * \text{Sales} / \text{sales_target}$
	40	investment availability	$\text{Sales} * \text{profitability}$
	41	profitability	$1 - \text{unit_cost} / \text{price}$
	42	price	$\text{MIN}(\text{unit_cost} * (1 + \text{desired_profitability}); \text{max_price})$
	43	economic sustainability	$1 - (\text{price} / \text{max_price})$
	44	product sustainability	$(\text{environmental_sustainability} + \text{social_sustainability} + \text{economic_sustainability}) / 3$

The parameters in the model and their values are reported in Table 5.3.

Table 5.3 Values of the stocks and converter

<i>Parameters</i>	<i>Values</i>
Compliance of Governmental Laws Ratio	0.290
Compliance of Governmental Laws	0.500
Employee Turnover Normal	0.250
Information Infrastructure	0.500
Capability of Human Resources Personnel	0.500
Employee Turnover	0.250
Information Infrastructure Ratio	0.226
Desired Profitability	0.150
Max Price	1.000
Average Sale	0.500
Level of Innovation Ratio	0.226
Level of Innovation Ratio on Flexibility	0.470
Production Capacity Ratio	0.258
Production Capacity Ratio on Flexibility	0.530
Sales	0.500
Level of Innovation	0.500

Equations related to the variables considered in economic, social and environmental dimensions to measure product sustainability are explained below.

Environmental Dimension

1. Environmental accidents variable has a negative relationship with compliance of governmental laws. When compliance of governmental laws scales up, environmental accidents variable decreases. The relationship was visualized for environmental accidents by using graphs in the system.
2. There is a negative relationship between product and energy waste variable and recycling variable. When recyclability increases, waste decreases evenly. The equation between these two variables in the model is represented by a negative relationship graph.
3. The company separates its investments according to particular percentages in four main branches. Compliance of governmental laws, which is one of these branches, is affected by different variables. Initially, compliance of governmental laws effect is calculated by multiplying the investment amount of the company with the rate which company previously determined for this particular investment.
4. Compliance of governmental laws rate is obtained by multiplying environmental sustainability with compliance of governmental laws effect.
5. To calculate the compliance of governmental laws change flow; stock amount which is not compliant with the law is multiplied by compliance of governmental laws rate which we obtained through the previous equation.
6. Pollution caused by organization, which is designated as a converter, has a positive linear relationship with environmental accidents. As environmental accidents increase, pollution rises evenly.
7. Recycling rate is expressed as a positive relationship which fluctuates evenly with the level of innovation in the system. An innovative approach in the entire life cycle of a product from design to delivery assures a high recyclability rate.

8. Working environment, which is another converter, is affected by compliance of governmental laws stock. As the compliance with the laws increases, the working environment risk level of the company is reduced. As the value in the stock rises, risks in the working environment climbs evenly and form a risk factor.
9. Environmental sustainability is the value which is affected by values of all the variables and parameters mentioned above, enabling the company to make progress by reducing waste and pollution levels.

Social Dimension

10. While an increase in working environment risk level effect and physical load effect on turnover values cause a rise in employee turnover normal value, increases in HRM performance value reduces employee turnover normal value. Employee turnover target value is calculated through multiplication of these effect rates.
11. There is a linear relationship between physical load effect on turnover and physical load rates.
12. Physical load equation is expressed as $(\text{Sales} / \text{Production Capacity}) * (1 - \text{worker_competency})$. Sales cause physical load for each unit that surpasses production capacity. In addition, as worker competency decreases, physical load increases in the same rate as the drop in worker competency. Therefore, each unit in sales that surpasses the production capacity creates a physical load in the same rate as the reduction in worker competency.
13. In the calculation of worker competency; worker competency is increased by effective training hours per employee. As employee turnover rate decreases, worker competency increases. Thus, the equation is expressed as $\text{effective training hours per employee} * (1 - \text{Employee_Turnover})$.
14. There is a linear relationship between effective training hours per employee and HRM performance.

15. HRM performance variable is displayed as the multiplication of company's usage of its information infrastructure by the capability of human resource personnel.
16. Employee turnover change variable equation is given as $(\text{employee turnover target} - \text{Employee Turnover}) * \text{Employee Turnover} / \text{employee turnover target}$.
17. Stakeholder engagement variable is obtained by multiplying company reputation by human resources performance as the variable influences both.
18. Company reputation proves to be in inverse proportion with customer claims.
19. Customer claims emerge due to inferiority in the quality level of the product, also each late delivery will result in a customer claim of its own.
20. Information infrastructure rate is a variable to determine how much of the investment is to be spent on information infrastructure.
21. Information infrastructure change is found by multiplying the insufficiency in the information infrastructure by investment amount devoted to the information infrastructure.
22. Order fulfillment errors decrease as information infrastructure is improved. Their relationship is visualized in a graph.
23. Late deliveries are directly proportional to the physical load effect created by order fulfillment errors on delivery.
24. Physical load effect on delivery is used to convert units.
25. Social sustainability; stakeholder engagement, worker competency and company reputation create a system reinforcing loop by influencing social sustainability. An increase in employee turnover rate negatively influences social dimension. Since social success of the firm means more employees loyal to the firm.

Economic Dimension

26. Quality level has a positive relationship with level of innovation and this is explained in a graph.
27. A positive linear relationship graph is given for the relation between efficiency and quality level.
28. The relationship between no-value added cost and customer claims is shown in a graph.
29. Production cost is expressed as $\text{No-Value Added Cost}/(1-\text{efficiency})$. Efficiency represents the ratio of value added costs in production cost. Thus, production cost is calculated by proportioning value added costs according to efficiency.
30. Unit cost increases as production cost rises. The relationship is presented in a graph.
31. Price effect variable is used to convert units.
32. Product obsolescence has a negative relationship with innovation level and this is given in a graph.
33. Level of innovation rate is found by multiplying company investments by level of innovation ratio.
34. Innovation change is calculated as a flow variable by multiplying level of innovation, which is considered as a stock, by level of innovation rate.
35. Production capacity rate; the speed at which the company increases its production capacity is determined by multiplying company investments by production capacity ratio.
36. Flow variable for capacity change is found through multiplication of production capacity ratio and production capacity rate. Flexibility is affected by production capacity at a rate of 0,53 and by level of innovation at 0,43.

37. Sales target; while an increase in the value of price effect and flexibility variables increases average sale value, product obsolescence has a reducing effect. Sales target value is calculated by the multiplication of these effect ratios.
38. Sales change is determined by multiplying sales target ratio and sales speed.
39. Investment availability is found by multiplying sales and profitability ratio.
40. Profitability is the difference between price and cost. Profitability ratio is the amount of profit in unit cost. Thus, the profitability ratio is calculated.
41. Price is obtained by the multiplication of unit cost and profitability target ratio.
42. Economic sustainability in calculation influences the price through risks and indicators, also negative and positive feedbacks, resulting in reduced price and economic sustainability.
43. Product sustainability; expressed as the average of the calculated rates for the three main dimensions

Model was run using the equations and initial values we defined above. The run time of the model was designated as 12 months. The results of the simulation are presented in different graphs, the first of which is product sustainability initially and later as environmental, economic and social which are the main three dimensions of sustainability (see Table 5.4).

Table 5.4 Results of the model

Dimensions Months		0	3	6	9	12
PRODUCT SUSTAINABILITY	Current Situation	0.536276	0.524709	0.540920	0.559629	0.579216
ECONOMIC SUSTAINABILITY	Current Situation	0.766406	0.746381	0.755538	0.755996	0.776946
SOCIAL SUSTAINABILITY	Current Situation	0.342422	0.307192	0.324886	0.347904	0.372249
ENVIRONMENTAL SUSTAINABILITY	Current Situation	0.500000	0.520555	0.542334	0.564988	0.588453

Initial value of the product sustainability was 0.536276. At the end of the simulation, the value reached 0.579216 in 12 months. Initial value of the economic, social and environmental sustainability were 0.766406, 0.342422, 0.500000 respectively. At the end of the simulation, the values reached 0.776946, 0.372249, 0.588453 in 12 months respectively.

Considering TBL approach, the 12-month behavior pattern of the environmental, economic, social and product sustainability are illustrated in Fig. 5.5.

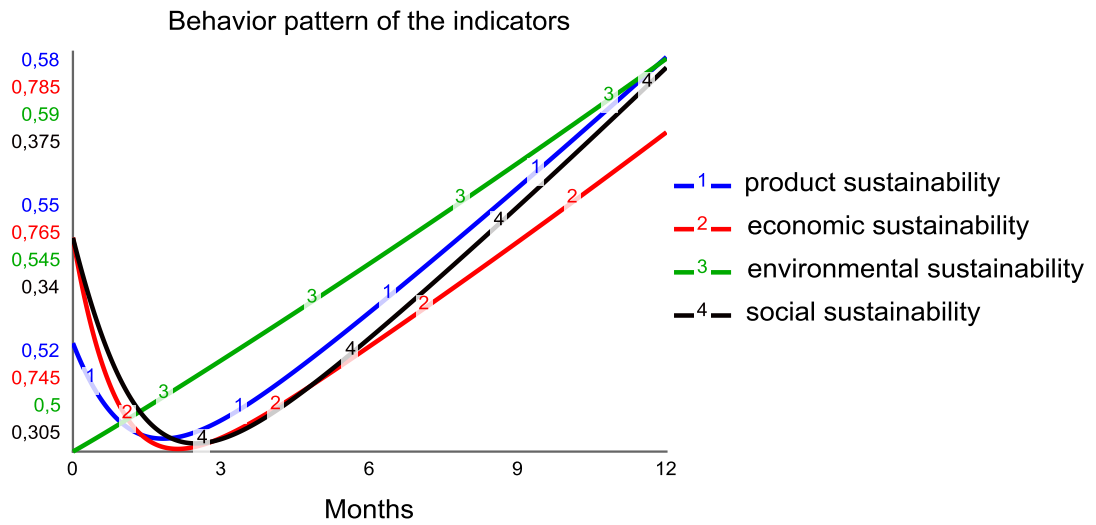


Figure 5.5 Behavior pattern of the indicator

Improvements in human resources performance decrease employee turnover rate and thus, social sustainability value is positively affected by these variables (see Fig. 5.6).

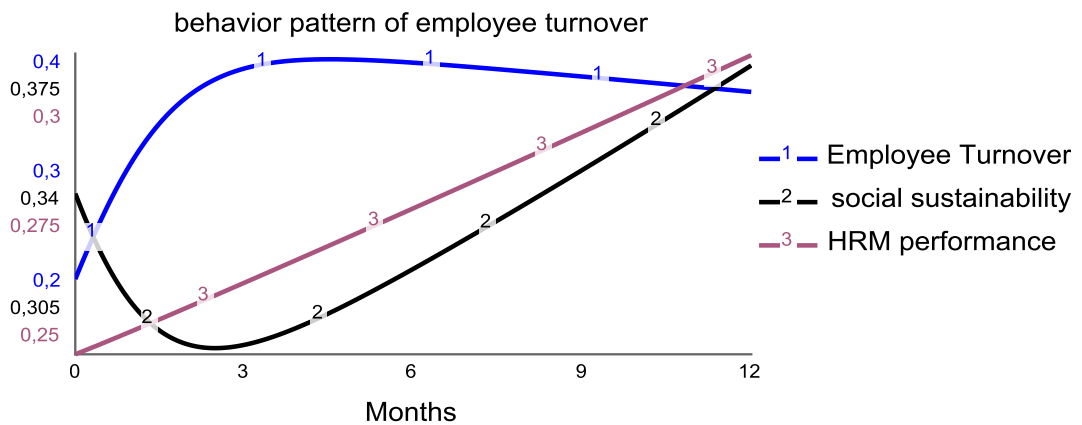


Figure 5.6 Behavior pattern of indicators regarding with social sustainability

In the system, customer claims variable is associated with both social and the economic dimension. In this respect, behavior pattern of customer claims over time was analyzed on these two dimensions. A decrease in customer claims positively affects both social and economic dimensions. The effect of customer claims on product sustainability is illustrated in Fig. 5.7.



Figure 5.7 Behavior pattern of customer claims

The company invests in four different branches. It directs its investments in order to keep up with the developments, reinforce its information infrastructure, increase its production capacity and finally to improve the systems necessary for regulatory laws. Consequently, as the amount of investment has increased, values related to the variables of social, environmental and economic sustainability have made progress in the 12-month period due to improvements in the three main dimensions (see Fig. 5.8)

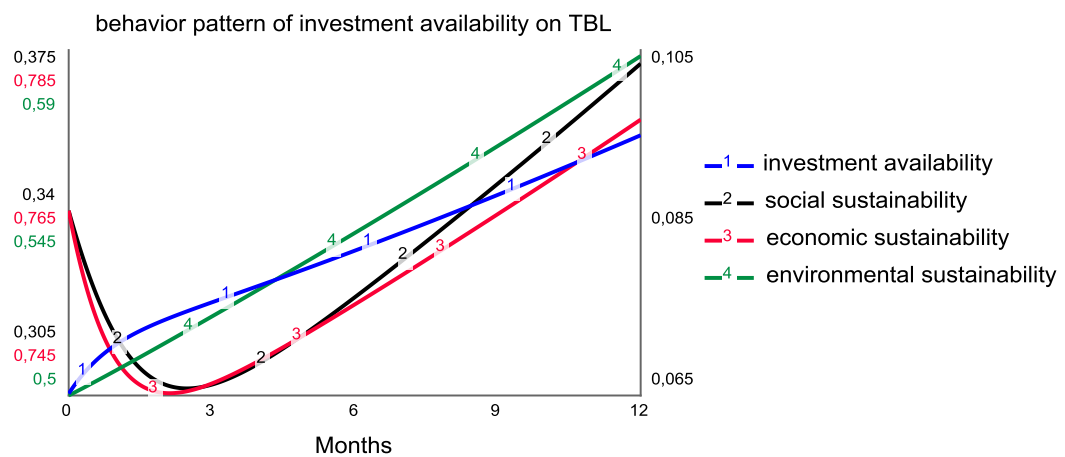


Figure 5.8 Behavior pattern of investment availability on TBL

The company's reputation affects the social and economic dimensions of sustainability. As the company gains reputation, shareholders' respect towards the company builds up, positively affecting the sustainability variable in the social dimension. As the quality level rise, fewer customer claims occur, which results in a higher level of reputation for the company. The behavior pattern of company reputation on economic and social sustainability are displayed in Fig. 5.9.

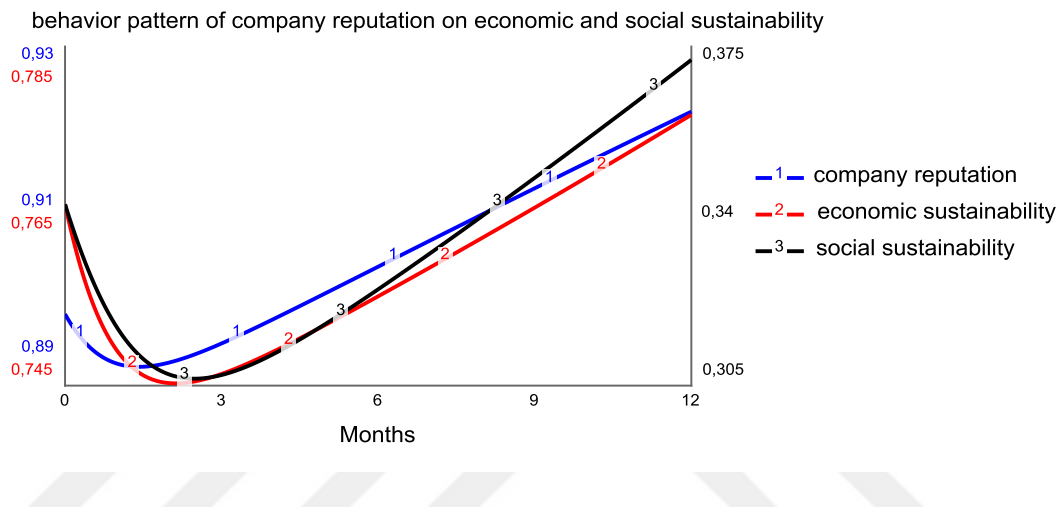


Figure 5.9 Behavior pattern of company reputation on economic and social sustainability

When the behavior graph of physical load variable is considered, a sharp increase in physical load can be observed until $t=2$ (see Fig. 5.10). In the time periods after the second month, a decreasingly growing change is visible. Accordingly, economic and social sustainability variables, which decreased until $t=2$, followed an upwards trend subsequently. When we examine the graph, it is observed that an increase in physical load affected the social and economic dimensions considerably at first. As a result of a gradual increase in the effects of other variables in the model on social and economic dimensions over time, a drop in the effect of physical load on these two major dimensions is seen.

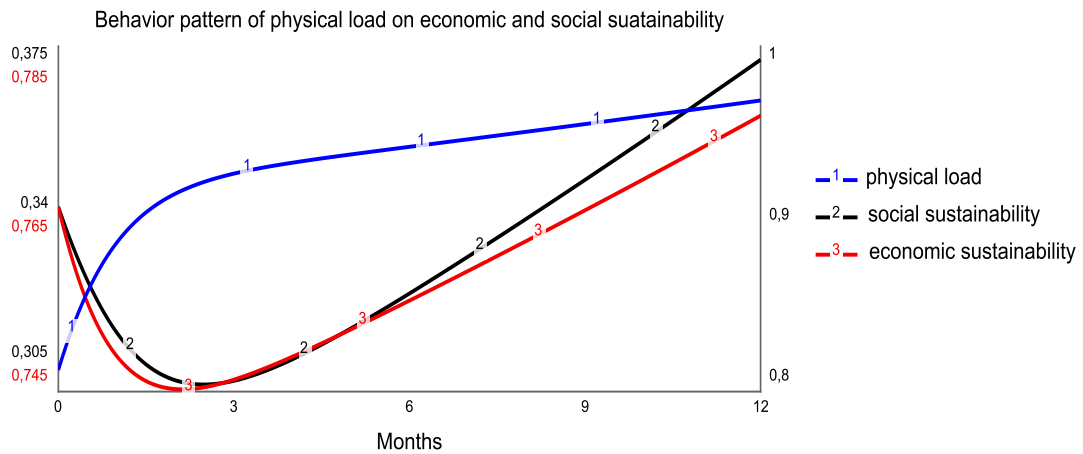


Figure 5.10 Behavior pattern of physical load on economic and social sustainability

Working environment risk level effect rate is associated with social and environmental dimensions in the model. As illustrated in Fig. 5.11, as the risk level in working environment and employee turnover rate decreases, social sustainability variable exhibits a gradually increasing behavior. As the compliance of the law increases, the risk in the working environment decreases and a positive effect of environmental sustainability realized.

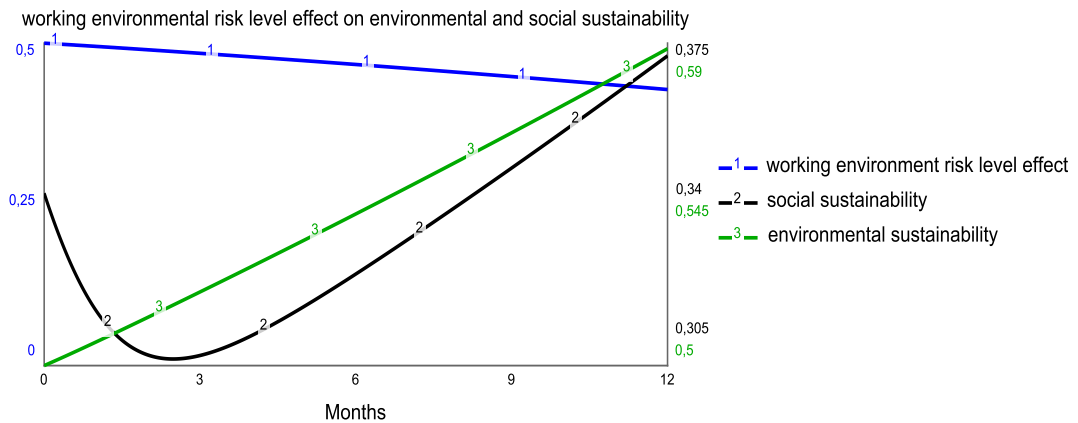


Figure 5.11 Behavior pattern of working environmental risk level effect

Improvements in the information infrastructure of the company influence both the social and environmental dimensions. Betterment of information infrastructure improves human resources performance, resulting in an increased social

sustainability. With the reinforcement of information infrastructure, order fulfillment errors can be decreased, and an increase in the environmental sustainability can be observed (see Fig. 5.12).

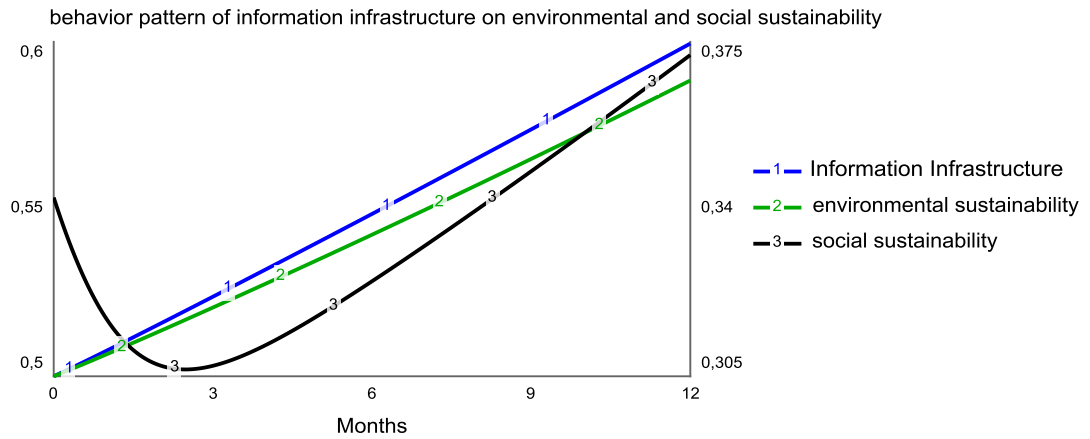


Figure 5.12 Behavior pattern of information infrastructure

5.2.4 Testing the Alternative Policies and Structures

In this step, two different scenarios have been analyzed. Firstly, system dynamics simulation model has been presented based on a real data set and the outputs in the above mentioned steps. The scenarios are defined in the following.

Scenario I:

As all competitive firms do, the firm in this application intends to measure product sustainability. The firm decided to minimize substantially the risks faced in the three major dimensions of product sustainability. Thus, the company needs to observe the behavior of product sustainability variable when the level of innovation and production capacity are increased.

As the level of innovation is improved, recycling becomes more possible and this improves the quality level of the product. When the company increases its recycling activities, which reduces waste, it also reinforces environmental sustainability as a result of feedback loops. Moreover, the company decreases the number of customer claims by increasing quality level which prevents returned products, indirectly

decreasing no-value added cost and allowing the company to gain reputation. As the reduction of no-value added cost influences economic dimension of sustainability through feedback loops, a higher reputation for the company affects the social aspect. Improvements in production capacity increases flexibility, and this increases sales and reinforcing the economic dimension by using feedback loops. An increase in the production capacity influences the social dimension due to another loop.

Current values in the system dynamics model are 0.5 for production capacity and 0.5 for the level of innovation. The company designated production capacity as 0.7 and the level of innovation as 0.8, and wanted to see the effects of these values on product sustainability and the three main dimensions.

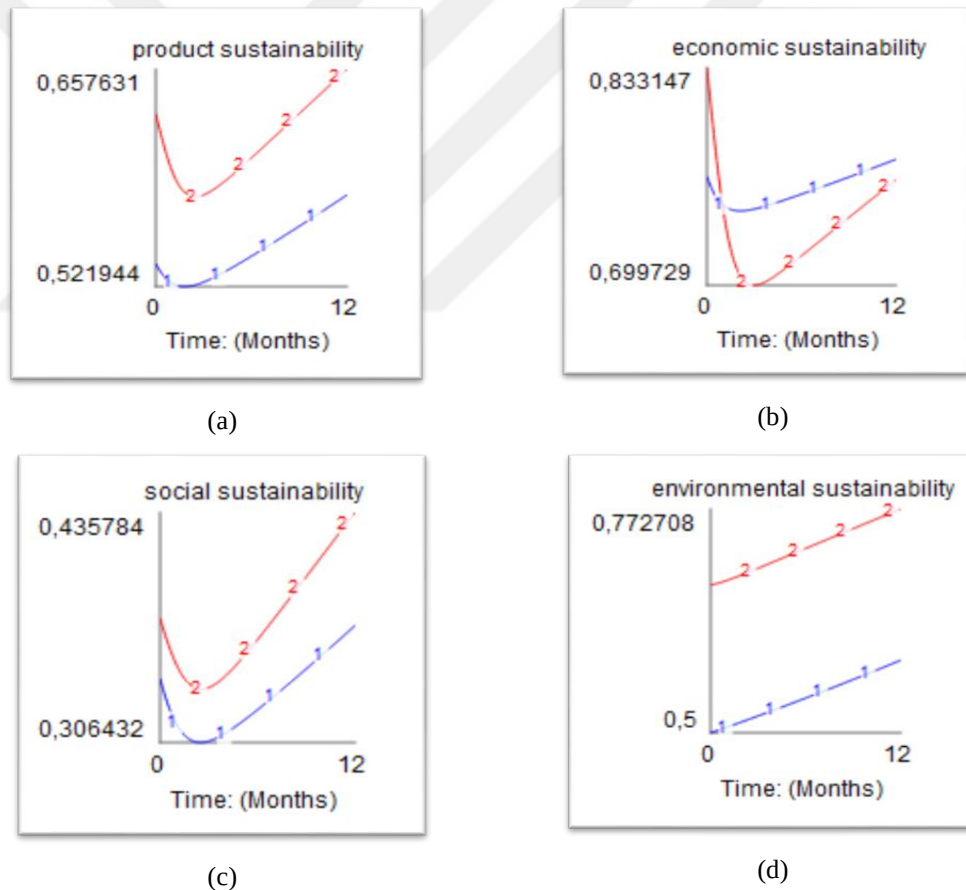


Figure 5.13 Behavior pattern of sustainability (a: product, b: economic, c: social, d: environmental)

The blue curve (1) shows current situation, the red curve (2) shows scenario I in the above graphs.

Thanks to the improvements, product sustainability followed a change as presented in Figure 5.13. The effects of improvements on economic, social and environmental dimensions are displayed in Fig. 5.13, respectively. Additionally, of the twelve-month simulation study, three-month change rates are presented in Table 5.5.

Table 5.5 Results of the model for scenario I

Dimensions Months		0	3	6	9	12
PRODUCT SUSTAINABILITY	Current Situation	0.536276	0.524709	0.540920	0.559629	0.579216
	Scenario I	0.629825	0.579200	0.602270	0.629955	0.657631
ECONOMIC SUSTAINABILITY	Current Situation	0.766406	0.746381	0.755538	0.765996	0.776946
	Scenario I	0.833147	0.699729	0.717792	0.741212	0.764400
SOCIAL SUSTAINABILITY	Current Situation	0.342422	0.307192	0.324886	0.347904	0.372249
	Scenario I	0.376327	0.337338	0.364286	0.399763	0.435784
ENVIRONMENTAL SUSTAINABILITY	Current Situation	0.500000	0.520555	0.542334	0.564988	0.588453
	Scenario I	0.680000	0.700532	0.724731	0.748889	0.772708

Initial value of the product sustainability before improvements was 0.536276. At the end of the simulation, the value reached 0.579216 in 12 months. While the initial product sustainability value was 0.629825 in Scenario I, it reached 0.657631 in 12 months by means of the improvements. If the company accomplishes suggested improvements by its effective decisions, the improvement rate will approximately reach 8%.

Economic sustainability decreased from 0.833147 down to 0.699729 in the first months of Scenario I. However, at the end of the 12-month period, it approached its initial level by reaching 0.764400 and started an upward trend from then on. It is possible to predict that a more meaningful improvement could be achieved when the simulation model is run for longer periods than 12 months. This fall we experienced is an expected result due to the fact that the company has to invest in order to make progress in these values and this results in a decrease in economic sustainability in the short-term. As a result of the effects of feedback loops in the simulation model, the company is to make profits out of its investments within a particular time period. As we have mentioned previously, accomplishment of this improvement will have a positive effect on long term economic sustainability of the company.

In the simulation model run, according to suggested improvements, environmental sustainability increased its initial value of 0.680000 up to 0.772708 at the end of 12 months. As a result of the suggested scenario analysis, an improvement of 9% is accomplished in environmental sustainability.

Scenario II:

In this scenario, according to the company's agenda, an application related to Industry 4.0 was implemented.

We can summarize the history of industry as the following; the first industrial revolution, Industry 1.0, emerged with the mechanization of production systems by utilizing water and steam power. The second industrial revolution, Industry 2.0, introduced mass production by means of electricity. The third industrial revolution brought about automation reinforced by the use of electronics and the development

of information technologies. The subject of this application, Industry 4.0, also referred to as the fourth industrial revolution involving automation systems, data exchange and production technologies. This structures also play an important role in smart factory applications. Since this revolution will allow collection of all data in production environment and make it possible to observe and analyze this information, it will lead to the emergence of more productive business models. The aim of Industry 4.0 is to produce higher quality, cheaper and faster products besides generating less waste.

Due to Industry 4.0, increasing production speed or a higher level of quality will not be sufficient to gain competitiveness so, not the most productive businesses but the ones which meet the needs of the customers most will prevail. Therefore, we have considered flexibility as the most important factor in the scenario we designed for the company. Moreover, as it is necessary in this scenario to deploy a capable work force and to increase the amount of investments for the application of Industry 4.0, “capability of human resources personnel” and “investment availability” variables are considered to be the main factors that influence the system. In Scenario II, the default values of 0.5 for these variables have been modified as 0.8 for “flexibility” and “investment availability”, and 0.7 for “capability of the human resources personnel”. The simulation model was run with these changes for a period of 12 months.

The results and simulation graphs are presented in the following.

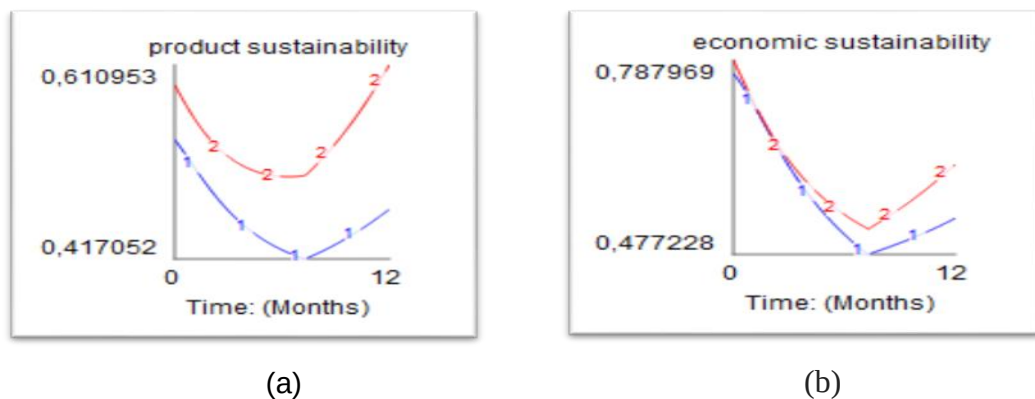
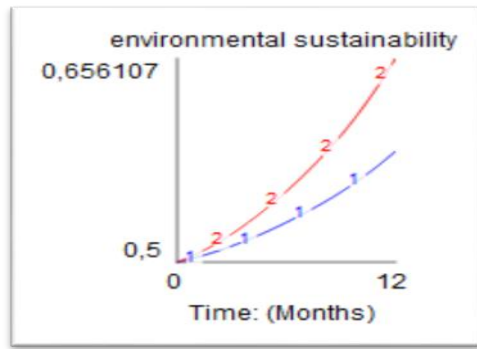
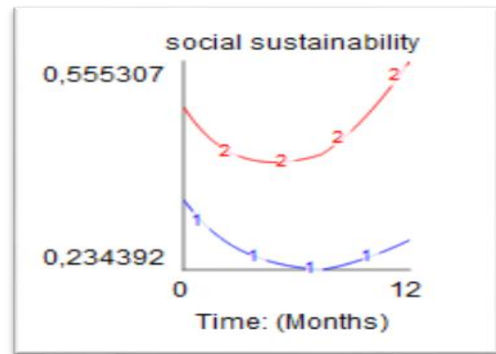


Figure 5.14 Behavior pattern of sustainability (a: product, b: economic)



(c)



(d)

Figure 5.14 continues (c: social, d: environmental)

The blue curve (1) shows current situation, the red curve (2) shows scenario II in the above graphs.

Table 5.6 Results of the model for scenario II

Dimensions Months		0	3	6	9	12
PRODUCT SUSTAINABILITY	Current Situation	0.536276	0.465155	0.426001	0.431611	0.466696
	Scenario II	0.591096	0.519150	0.499299	0.532578	0.610953
ECONOMIC SUSTAINABILITY	Current Situation	0.766406	0.618300	0.509109	0.495384	0.535088
	Scenario II	0.787969	0.627139	0.540857	0.550049	0.621445
SOCIAL SUSTAINABILITY	Current Situation	0.342422	0.264899	0.238489	0.245817	0.280011
	Scenario II	0.485318	0.408752	0.402862	0.450665	0.555307

Table 5.6 continues

ENVIRONMENTAL SUSTAINABILITY	Current Situation	0.500000	0.512267	0.530405	0.553631	0.584988
	Scenario II	0.500000	0.521559	0.554178	0.597019	0.656107

The company observed the effects of increased values of flexibility, capability of human resources personnel and investment availability on product sustainability and three main dimensions, before applying Industry 4.0.

The value of product sustainability level increased from 0.466696 to 0.610953 at the end of the 12-month period. In addition, the economic sustainability value increased from 0.535088 to 0.621445, social sustainability from 0.280011 to 0.555307 and finally environmental sustainability from 0.584988 to 0.656107. Furthermore, of the other variables influenced in the system, employee turnover rate initially increased and then started to decline. It was observed that the information infrastructure developed and the innovation level of the company increased. Production capacity and efficiency also improved.

Through the analysis of the second scenario, possible consequences that will emerge when Industry 4.0 is applied in the company were presented for product sustainability, its three main dimensions and other affected variables in the system.

5.2.5 Discussion

As a conclusion, for scenario I, it has been observed that increasing the production capacity of the company and maintaining the production by emphasizing innovation have led to improvements on both product sustainability and on the main dimensions of product sustainability in the 12-month period.

For scenario II, it has observed that towards Industry 4.0 applications, when flexibility, capability of human resources personnel and investment availability variables were increased, product sustainability and other risks are positively affected.

CHAPTER SIX

CONCLUSIONS

In this thesis, the main focus is to develop a risk-oriented approach in measuring product sustainability. In order to achieve this, the approaches considering the risks related to three dimensions of sustainability as a whole must be used. However, previous studies in this field do not consider the three base line structure of sustainability in a dynamic way. Considering this fact, three main dimensions of sustainability were considered and system dynamics modelling approach was used to design a dynamic measurement structure for product sustainability.

A real-life application was presented to prove applicability of the suggested approach. 31 different risks and indicators which were identified for the company were taken into account in the designed model. A causal loop diagram was created to observe risk interactions by using Vensim software and then, by using the relationships considered in a causal loop diagram, a system dynamics model was designed. One of the software tools used for system dynamics modelling, Stella Architect was utilized. Product sustainability was evaluated through graphs visualized by analyzing the model results.

Two different scenarios were used to see the short term consequences of company's current decisions on sustainability and its three main dimensions. In the first scenario, the effects of higher "production capacity" and "level of innovation" on product sustainability were examined. As the production capacity of the company and level of innovation increase, improvements on both product sustainability and on the main dimensions of product sustainability increase. The second scenario was designed for examining the prospective application of Industry 4.0. The model was simulated with increased values of "flexibility", "capability of human resources personnel" and "investment availability" variables. By analyzing the results of scenario II on product sustainability and other risks, it was concluded that realization of Industry 4.0 applications could be an effective strategy for the company for increasing the product sustainability and consequently gaining more competitive advantage.

As a future study, this study can be improved by prospering risks and indicators for three main sustainability dimensions. Relations between these three dimensions and variables can be improved. In addition, as the risks handled by the model are generic, the proposed system dynamic model can be used by different companies operating in different sectors. Furthermore, companies can apply this model to examine different future scenarios, and consequently to make better decisions.



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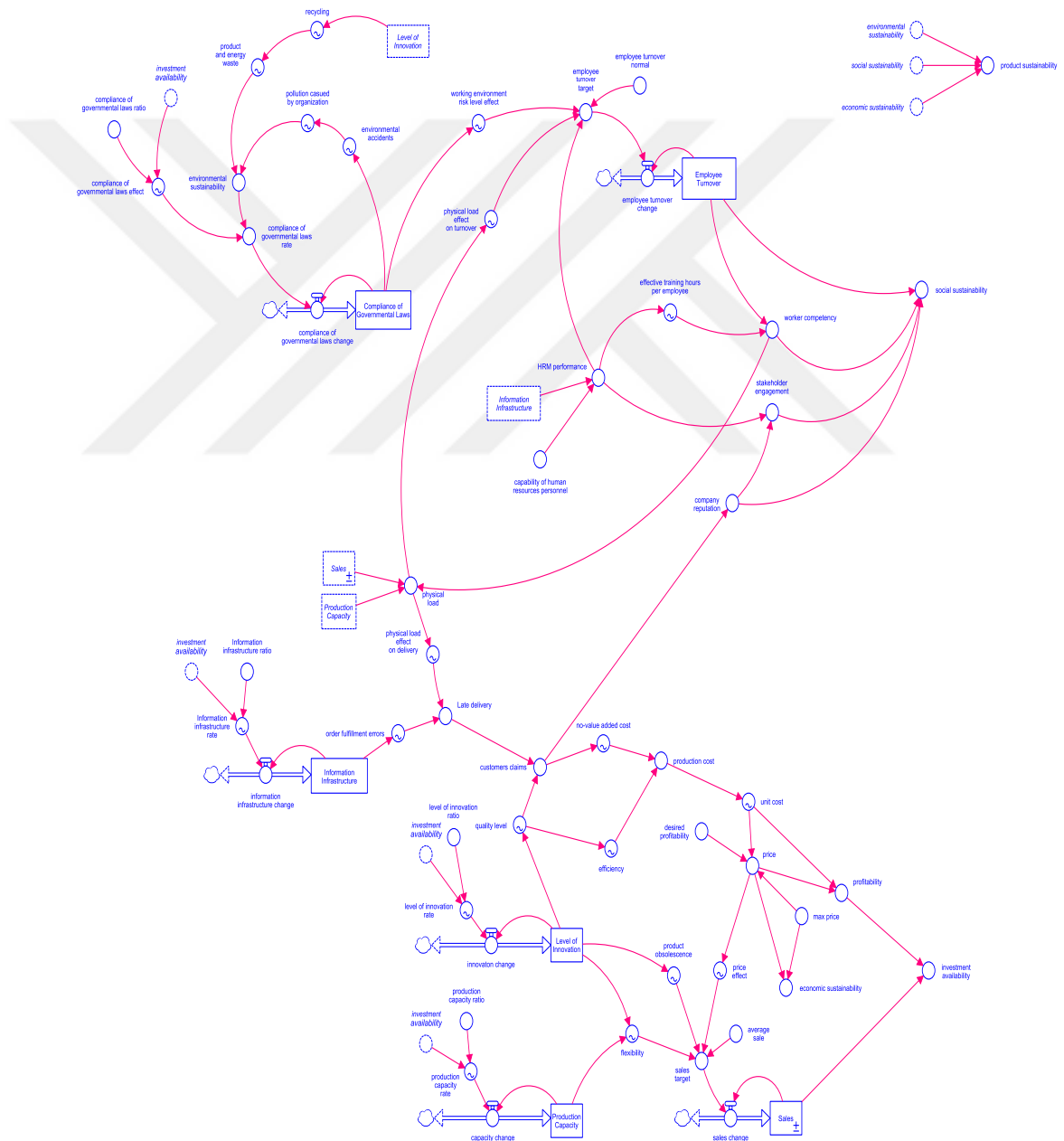
APPENDICES

APPENDIX 1: STELLA Model

APPENDIX 2: STELLA Model Equations

APPENDIX 3: STELLA Model for Scenario II

APPENDIX 1: STELLA Model



APPENDIX 2: STELLA Model Equations

Top-Level Model:

$\text{Compliance_of_Governmental_Laws}(t) = \text{Compliance_of_Governmental_Laws}(t - dt) + (\text{compliance_of_governmental_laws_change}) * dt \{ \text{NON-NEGATIVE} \}$

INIT Compliance_of_Governmental_Laws = 0,5

INFLOWS:

$\text{compliance_of_governmental_laws_change} =$

$(1 - \text{Compliance_of_Governmental_Laws}) * \text{compliance_of_governmental_laws_rate}$

$\text{Employee_Turnover}(t) = \text{Employee_Turnover}(t - dt) + (\text{employee_turnover_change})$

$* dt \{ \text{NON-NEGATIVE} \}$

INIT Employee_Turnover = 0,25

INFLOWS:

$\text{employee_turnover_change} = (\text{employee_turnover_target} - \text{Employee_Turnover})$

$* \text{Employee_Turnover} / \text{employee_turnover_target}$

$\text{Information_Infrastructure}(t) = \text{Information_Infrastructure}(t - dt)$

$+ (\text{information_infrastructure_change}) * dt \{ \text{NON-NEGATIVE} \}$

INIT Information_Infrastructure = 0,5

INFLOWS:

$\text{information_infrastructure_change} =$

$(1 - \text{Information_Infrastructure}) * \text{Information_infrastructure_rate}$

$\text{Level_of_Innovation}(t) = \text{Level_of_Innovation}(t - dt) + (\text{innovaton_change})$

$* dt \{ \text{NON-NEGATIVE} \}$

INIT Level_of_Innovation = 0,5

INFLOWS:

$\text{innovaton_change} = (1 - \text{Level_of_Innovation}) * \text{level_of_innovation_rate}$

$\text{Production_Capacity}(t) = \text{Production_Capacity}(t - dt) + (\text{capacity_change})$

$* dt \{ \text{NON-NEGATIVE} \}$

INIT Production_Capacity = 0,5

INFLOWS:

$\text{capacity_change} = (1 - \text{Production_Capacity}) * \text{production_capacity_rate}$

$\text{Sales}(t) = \text{Sales}(t - dt) + (\text{sales_change}) * dt$

INIT Sales = 0,5

INFLOWS:

$\text{sales_change} = (\text{sales_target} - \text{Sales}) * \text{Sales} / \text{sales_target}$

$\text{average_sale} = 0,5$

$\text{capability_of_human_resources_personnel} = 0,5$

$\text{company_reputation} = 1 - \text{customers_claims}$

$\text{compliance_of_governmental_laws_effect}$

$= \text{GRAPH}(\text{investment_availability} * \text{compliance_of_governmental_laws_ratio})$

$(0,000, 0,000), (1,000, 1,000)$

$\text{compliance_of_governmental_laws_rate}$

$= \text{compliance_of_governmental_laws_effect} * \text{environmental_sustainability}$

$\text{compliance_of_governmental_laws_ratio} = 0,290$

$\text{customers_claims} = (1 - \text{quality_level}) * \text{Late_delivery}$

$\text{desired_profitability} = 0,15$

$\text{economic_sustainability} = 1 - (\text{price} / \text{max_price})$

effective_training_hours_per_employee_index = GRAPH(HRM_performance)
 (0,000, 0,000), (1,000, 1,000)
 employee_turnover_normal = 0,25
 employee_turnover_target = employee_turnover_normal
 * (1+working_environment_risk_level_effect)
 * (1+physical_load_effect_on_turnover) * (1 - HRM_performance)
 environmental_accidents = GRAPH(Compliance_of_Governmental_Laws)
 (0,000, 1,000), (1,000, 0,000)
 environmental_sustainability = 0,4 *(1-pollution_casued_by_organization) +
 0,6 *(1-product_and_energy_waste)
 flexibility = GRAPH(0,47* Level_of_Innovation + 0,53 * Production_Capacity)
 (0,000, 0,000), (1,000, 1,000)
 HRM_performance = capability_of_human_resources_personnel
 * Information_Infrastructure
 Information_infrastructure_rate
 = GRAPH(investment_availability*Information_infrastructure_ratio)
 (0,000, 0,000), (1,000, 1,000)
 Information_infrastructure_ratio = 0,226
 investment_availability = Sales * profitability
 Late_delivery = order_fulfillment_errors * physical_load_effect_on_delivery
 level_of_innovation_rate
 = GRAPH(investment_availability*level_of_innovation_ratio)
 (0,000, 0,000), (1,000, 1,000)
 level_of_innovation_ratio = 0,226
 max_price = 1
 "no-value_added_cost" = GRAPH(customers_claims)
 (0,000, 0,000), (1,000, 1,000)
 order_fulfillment_errors = GRAPH(Information_Infrastructure)
 (0,000, 1,000), (1,000, 0,000)
 physical_load = (Sales / Production_Capacity) * (1 - worker_competency)
 physical_load_effect_on_delivery = GRAPH(physical_load)
 (0,000, 0,000), (2,000, 1,000)
 physical_load_effect_on_turnover = GRAPH(physical_load)
 (0,000, 0,000), (2,000, 1,000)
 pollution_casued_by_organization = GRAPH(environmental_accidents)
 (0,000, 0,000), (1,000, 1,000)
 price = MIN(unit_cost * (1+desired_profitability); max_price)
 price_effect = GRAPH(price)
 (0,000, 1,000), (1,000, -1,000)
 product_and_energy_waste = GRAPH(recycling)
 (0,000, 1,000), (1,000, 0,000)
 product_obsolescence = GRAPH(Level_of_Innovation)
 (0,000, 1,000), (1,000, 0,000)
 product_sustainability = (environmental_sustainability + social_sustainability
 + economic_sustainability) / 3
 production_capacity_rate
 = GRAPH(investment_availability*production_capacity_ratio)
 (0,000, 0,000), (1,000, 1,000)

```

production_capacity_ratio = 0,258
production_cost = "no-value_added_cost"/(1-efficiency
efficiency = GRAPH(quality_level)
(0,000, 0,000), (1,000, 1,000)
profitability = 1-unit_cost/price
quality_level = GRAPH(Level_of_Innovation)
(0,000, 0,000), (1,000, 1,000)
recycling = GRAPH(Level_of_Innovation)
(0,000, 0,037), (1,000, 1,000)
sales_target = average_sale * (1+price_effect) * (1+flexibility)
* (1-product_obsolescence)
social_sustainability = stakeholder_engagement
*company_reputation+ worker_competency *(1 - Employee_Turnover)
stakeholder_engagement = company_reputation * HRM_performance
unit_cost = GRAPH(production_cost)
(0,000, 0,000), (1,000, 1,000)
worker_competency = effective_training_hours_per_employee_index
* (1 - Employee_Turnover)
working_environment_risk_level_effect
= GRAPH(Compliance_of_Governmental_Laws)
(0,000, 1,000), (1,000, 0,000)
{ The model has 59 (59) variables (array expansion in parens).
In root model and 0 additional modules with 0 sectors.
Stocks: 6 (6) Flows: 6 (6) Converters: 47 (47)
Constants: 9 (9) Equations: 44 (44) Graphicals: 20 (20)}

```

APPENDIX 3: STELLA Model for Scenario II

