DECISION MODELS FOR SUSTAINABLE MANUFACTURING SYSTEMS

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In this research, three interrelated problems of the product lifecycle decision making are studied from the perspective of sustainable manufacturing: waste reduction in manufacturing, green product deployment strategies and product upgrade investment decision making. Mathematical models that are validated by industrial data or numerical examples are developed. These models can assist various stakeholders in making the rational decisions at corresponding product lifecycle stages.

The first part of this research focuses on identifying the optimal decisions in waste reduction during the product design and manufacturing phase. A multi-objective decision making model with Pareto frontier chart is developed to help decision makers identify the optimal project portfolios for the implementation of Lean and Six Sigma concepts. This model is validated in a mid-sized semi-conductor company.

The second segment of this research concentrates on the market analysis for green products. Game theoretic models that analyze the market competition and the dynamic equilibrium as companies enter and leave the market are developed. Sensitivity analyses are then conducted to analyze the factors for the healthy growth of green products in a competitive market. This model can provide engineering and managerial insights for green production industry and public policy makers in order to help the society move towards the goal of sustainable manufacturing.

The last part of this research focuses on identifying the best investment decisions at each phase of a product's lifecycle after it has been released to the market. This problem is formulated as a Markov decision process (MDP) model where optimal sequential investment decisions are made based on the product lifecycle phases and market demand fluctuations so as to maximize the long-term profit.

In summary, this research concentrates on developing and validating mathematical models of the product lifecycle decision making within the context of sustainable manufacturing. Industrial case studies are utilized to validate the mathematical models and develop guidelines for strategic decision making for various stakeholders. This study contributes to the body of knowledge in decision making for manufacturing companies by developing novel quantitative models for decision making through a product's lifecycle.

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PREFACE

I would like to thank my Ph. D advisor Dr. Bopaya Bidanda, for his motivation, inspiration and encourage throughout my doctoral study. He is not only a fascinating research advisor in my study but also an excellent mentor in life where he sets an example of a successful and honorable person in every aspect. He is as caring as a parent and as frank as a best friend. He has helped me become a better person than I could ever be without him, but he probably could not even realize how much I have learned from him and how much I appreciate everything he has done for me.

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1.0 INTRODUCTION

Making the "right" decisions at each stage of a product's lifecycle is important to the healthy, sustainable development of the manufacturing industry. Product lifecycle theory has been a key principle in the studies of technology innovation and has been recognized by leading management theorists as a useful tool for strategic decision making [1]. Product lifecycle decision making systems involve multiple stakeholders including manufacturers, distributors, service providers, the regulatory agencies, etc.

As part of the societal development process, government and civil society took economic growth and social equity as the primary concern for a long period of time [2]. Concerns about the environment started in the late 1960s in the U.S. and quickly spread worldwide afterwards [3]. Government and society began to realize the interconnections between the environment, economy and social well-beings.

The 1987 World Commission on Environment and development (WCED) acknowledged the trend by defining a new term — sustainable development [4]. Since then, the concept has made great impacts in the political, economic and social sectors [5]. Following the trend, the manufacturing sector welcomes a new term — sustainable manufacturing. It was generally recognized as — "using benign chemicals where possible, incorporating smart reuse and recycling practices and delivering products without exhausting resources, at a lower cost and a reduced environmental impact [6]".

In this research, principles of industrial engineering are utilized to develop rational decision making mechanisms when there are conflicts and trade-offs between various stakeholders. Three interrelated aspects of product lifecycle decision making are studied from the perspective of sustainable manufacturing: waste reduction in manufacturing, green product deployment strategies and product upgrade investment decision making. Mathematical models along with algorithms and validations for each of these problems are developed to assist various stakeholders in making the rational decisions at corresponding product lifecycle stages.

1.1 RESEARCH MOTIVATION

With the growing concern about the global warming and environmental issues, sustainable manufacturing and efficient resource utilization are gaining popularity with significant potential in theoretical study as well as industrial applications. Based on Department of Commerce report on Sustainable Manufacturing Initiative, “sustainable manufacturing is defined as the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers[7]”. Therefore, sustainable manufacturing can also be viewed to be the implementation of a series of company projects throughout a product’s lifecycle.

Angell and Klassen [8] propose an agenda for research on integrating environmental issues into the mainstream in operations management. Operations management issues in the environmental management area are summarized in the paper and two distinct perspectives, i.e., the constraint and component perspectives are identified to characterize the study and present the importance of sustainable development for the whole society. Nowadays, a growing number of societal sectors, including construction and manufacturing, are concerned about the long-term sustainable development in addition to the economical profit and impacts.

Toyota Motor Corporation is one of the pioneer car manufacturers launched the sustainable manufacturing initiatives [9]. Toyota established the “Toyota Environmental Action Plan” in 1993 and after that a series of company wide sustainable manufacturing initiatives have been implemented. From the organizational framework, material procurement to production process and management of environmentally hazardous substance, the company has been working towards the goal of “Zero Emission”.

Sustainable development was generally referred to as “passing on to the future generations a stock of capital that is at least as big as the one that our own generation inherited from the previous generations” [10]. The concept of “Triple Bottom Line: People, Planet, Profit” defines the criteria of organizational and societal success [11]. It is used widely to describe the ultimate goal of sustainability. Following the same concepts, the definition of sustainable manufacturing acknowledges that the development in the social, environmental and economic dimensions are of equal importance towards the development of society [12]. This matches the “Triple Bottom Line” concept perfectly from the three aspects of human capital, resource capital and economic benefits. To achieving the goal of sustainable manufacturing requires supportive actions from all of the three aspects: economic prosperity, environmental sustainability and social equity.

The scope and relationship of the three aspects are shown in figure 1 [13].

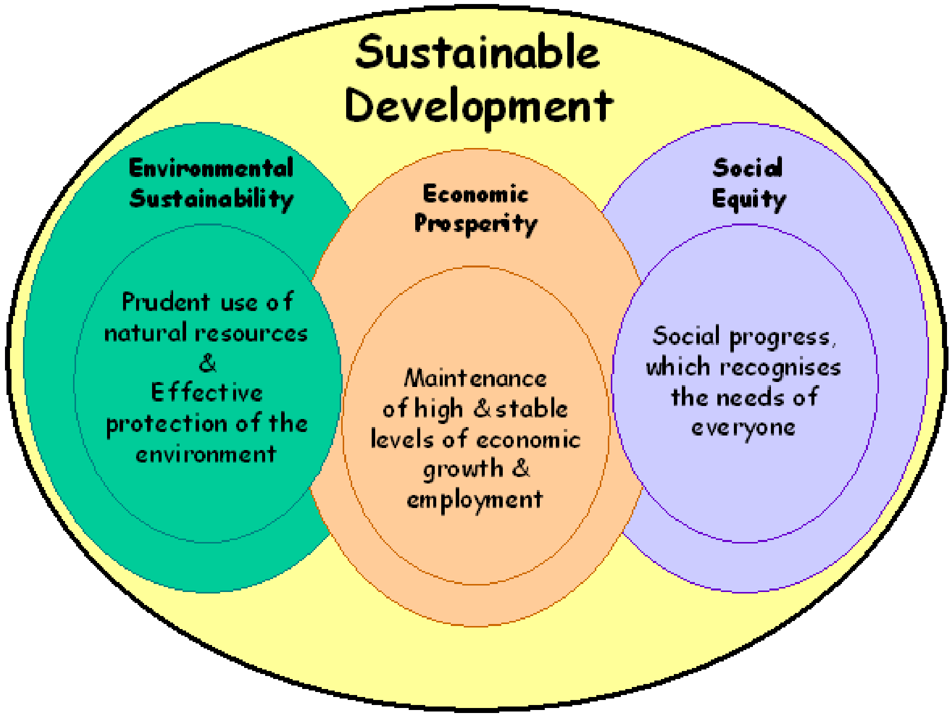

Figure 1. Scope of Sustainable Development [13]

Since the resources are limited, the studies on sustainable utilization of the available resources have been prevailing. There has been an extensive collection of literature on how to achieve the goal of sustainable development in various societal sectors. Otterpohl et al. did a study on the sustainable water and waste management in urban areas [14]. They proposed various realistic methods of using water and treating waste in a sustainable manner in the urban environment.

In California, there are many sustainable manufacturing initiatives, such as green building. For example, the government executive board sets a goal of reducing energy use in the state-owned buildings by 20 percent by 2015 (from a 2003 baseline) and encourages the private commercial sector to set the same goal as well [15]. In the power/energy sector, Department of

Energy has launched many green initiatives to improve energy efficiency and introduce renewable/clean energy in various states [16]. Some of the goals are: 5% of nation's electricity is generated from renewable/clean resources by 2020; the U.S. use of bio-based products and bio-energy is tripled by 2010.

In New York State, the Pollution Prevention Institute and Rochester Institute of Technology (RIT) conducted a case study on Lean, Energy and Environment (LE2) in Tecmotiv USA Inc.[17]. The LE2 program comes from two previous program (the Lean and Environment program and the Lean and Energy program) developed by EPA. This concept combines the practical techniques and strategies to achieve lean manufacturing with the overall energy use, environmental cost and risk.

In addition, the pressure on companies to incorporate the principles of sustainable manufacturing into business decision making is growing. The concept of "3R: reduce, reuse, and recycle" came out in this process. Many European countries require their manufacturers take back their used products and dispose them properly (without negative effects to the environment). In addition, remanufacturing companies emerge in manufacturing industry. They take used products from customer, refurbish/recycle them and resell them to make profits. These companies can either be a separate company or part of the traditional manufacturer. This is often referred to as reverse logistics or closed-loop supply chain management.

Much research has been conducted in the reverse logistics and closed-loop supply chain management field. LN Van Wassenhove, V. D. R. Guide and M Fleischmann [18,19,20,21,22,23,24,25,26] are seminal researchers in the closed-loop supply chain and remanufacturing arena. They initiated the strategic and managerial leveled studies and conclude that remanufacturing, if implemented properly, can be beneficial for both the company and the entire society. Later, quantitative supports were provided based on mathematical models. Studies were focused on how the closed-loop supply chain and reverse logistics should be implemented in the manufacturing sector. Case studies and surveys were also carried out to provide application support for quantitative studies in the closed-loop supply chain and reverse logistics areas.

Lifecycle analysis /lifecycle assessment bears the similar concept with the closed-loop product lifecycle management. In LCA, detailed examination of the lifecycle of a product is conducted and analyzed to help decision making. This lifecycle analysis was brought out largely due to the increased environmental awareness from the part of public, industry and governments [27]. Since then, it has been a powerful tool to assist manufacturers to analyze the processes and improve products, help government/regulator form legislations and even inform consumers to make better choices. One of the most popular tools in LCA is lifecycle costing analysis [28], in which environmental issues and green values are taken into account. Nowadays, lifecycle analysis is being recognized as a method in sustainable product management arena.

Traditional methods in the sustainable product lifecycle management are often conceptual. Labuschagne and Brent [29] point out that current project management frameworks do not effectively address the three goals of sustainable development (i.e., social equity, economic efficiency and environmental performance). They outline the needs of sustainable development and propose several ways to achieve the true sustainable lifecycle management in the manufacturing sector.

Most existing studies on sustainable development have been statistical summaries and case studies. D. Sperling et al. analyzed the impacts of regulations on automobile industry and the consumers' choices [30]. This study provides insights into the impacts of governmental regulation and they found that the cost imposed on vehicles due to regulations have been significant. R. Wiser et al. [31] carried out an assessment on green power market in the real competition. Pilot programs in four states (California, Massachusetts, Rhode Island, and Pennsylvania) have shown that green power marketing is an effective way of attracting customers in the retail residential sector.

However, conceptual and qualitative studies are often not enough to support decision making process. Therefore, there exists a great need to make rational decisions in the achievement of sustainable development. Quantitative supports are essential to make the right decisions in the complex system. This is the major motivation of this dissertation study. In this dissertation, quantitative models are developed to assist decision makers to make the "right" decisions at different stages in the product lifecycle. Model validations are carried out based on industrial data and numerical examples.

1.2 PROBLEM STATEMENT

The first step to achieve sustainable manufacturing in practice is the awareness of the economic, environmental and social impacts of the activities throughout a product's lifecycle evolution process. Understanding of the impacts of the activities can therefore ensure the achievement of the societal benefits in each of the three aspects of sustainable development (economic prosperity, environmental sustainability and social equity). This dissertation has the intention of providing quantitative models that will support company executives, policy makers as well as consumers to make the right decisions in the process of sustainable manufacturing, in other words, achieving economical prosperity as well as environmental sustainability and social equity in the manufacturing sectors.

This dissertation research studies three interrelated aspects of product lifecycle decision making from the perspective of sustainable manufacturing: waste reduction in manufacturing, green product deployment strategies and product upgrade investment decision making. Mathematical models for each of these problems are developed to assist various stakeholders in making the rational decisions at corresponding product lifecycle stages.

The linkage between these segments loosely follows the evolution of the product through its lifecycle as shown in figure below. Novel quantitative approaches for the decision making through a product's lifecycle are developed along with algorithms and validations. Validations are carried out based on available data either from a real industrial application or from the public domain. The availability of the data for model demonstration and validation serves as another reason to choose these problems for my dissertation study.

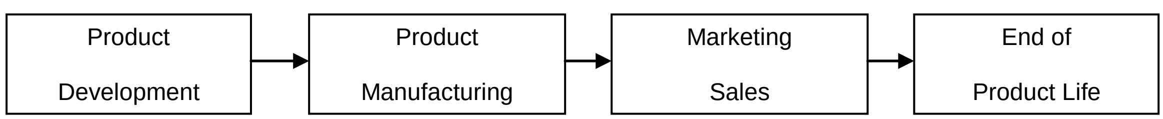

Figure 2. Product Lifecycle Evolution

1.2.1 Project Portfolio Selection to Implement Lean and Six Sigma Manufacturing

The first part of this research focuses on identifying the optimal decisions in waste reduction in the product manufacturing phase. The application of Lean and Six Sigma has made significant impacts in both academic research and industry over the last decades. One of the complex decisions in the lean and waste reduction is project portfolio selection with a limited amount of available resources.

In the Lean and Six Sigma project selection process, there are various objectives need to be considered. Therefore, in this part of the dissertation, a multi-objective decision making model with Pareto frontier chart is developed.

The major contribution of this study is objective function formulation. In the multi-objective model formulation, a novel way of defining the objective function for integrated benefit is developed. In addition, the simplification of the objective function for integrated benefit makes the mathematical programming solvable. This model formulation provides a new and better mechanism for project portfolio selection. It can assist the decision makers identify the optimal project portfolio for implementation of Lean and Six Sigma concepts. The mathematical model is validated by industrial data from a mid-sized semi-conductor company. This model can be extended to other industrial applications where trade-off decisions have to be made between multiple objectives.

1.2.2 Game Theoretical Models for Market Competition Analysis in Green Production

The second segment of this research concentrates on the market analysis for sustainable/green products. As global awareness and concern for the environment increase, many policy makers, stakeholders and business leaders have begun to call on the business community to play a major role in moving the global economy development toward sustainable development. Sustainable manufacturing encompass both sustainable manufacturing process and the outcome of the manufacturing process: sustainable products. The mathematical model developed in this part of my dissertation can be applied for both scenarios of the sustainable manufacturing field.

Market competitiveness is an important factor for corporate strategic decision making. In this part of the research, game theoretic models are developed to analyze the market competition. The dynamic equilibrium is also studied as companies enter and leave the market. A sensitivity analysis is conducted to analyze the factors for the healthy growth of green products in the competitive market. Game theoretic models can provide detailed engineering and managerial insights on how to help green production to survive in the fierce market competition. In addition, the effects of the government and regulatory organizations interventions are considered, such as tax reduction/subsidy for green products, standards on carbon dioxide emission and education for public awareness.

The major contribution of this game theory study is to provide a new perspective to analyze the market competition between green and ordinary production industries. The dynamic equilibrium and sensitivity analysis address more realistic market scenarios. The mathematical model can provide both engineering and managerial insights for the manufacturers, consumers and the government regulatory departments.

1.2.3 Long Term Profit-driven Decision Making in Product Market Lifecycle Management

The last part of this research focuses on identifying the best investment decision at each phase of a product's lifecycle after it has been released to the market. This is one of the key elements in product upgrade and marketing strategies. This mathematical model considers a sequential decision making process through each stage of the product lifecycle after its release to the competitive market. This problem is formulated as a Markov decision process (MDP) model where optimal sequential investment decisions are made based on the product lifecycle phases and market demand fluctuations so as to maximize the long-term profit.

The major contribution of this study is the application of Markov Decision Process (MDP) methodology in the lifecycle evolution decision analysis. Managerial Insights can be derived from the model and help decision makers identify best strategies. It is a general model formulation that can be adapted for a multitude of industries and products. In addition, for future research direction, reverse logistics concept can also be incorporated into the model for decision making in closed-loop supply chain management systems.

In summary, this research concentrates on developing and validating mathematical models of the product lifecycle decision making in the context of sustainability. There are three interrelated parts of this research and the linkage between these segments loosely follows the evolution of the product through its entire lifecycle. Industrial case studies are utilized to validate the mathematical models and develop guidelines for strategic decision making for manufacturing corporations. This study contributes to the body of knowledge in decision making for manufacturing companies by developing novel, validated, quantitative models for decision making through a product's lifecycle.

The remainder of this dissertation is organized as follows: chapter 2, 3 and 4 correspond with each of the three segments of this research, including the literature review, mathematical models, solution techniques and validation applications. Chapter 2 introduces the multi-objective model for project selection to implement Lean and Six Sigma concepts. Chapter 3 discusses the game theoretical models developed to analyze competitive market with both green and ordinary production sectors. Guidelines and suggestions are provided based on the analysis and numerical examples. Chapter 4 considers the decision making after the product has been released to the market. Markov decision processes (MDP) methodology is utilized to formulate the problem. Engineering and managerial insights are derived based on the case study in the digital camera industry. The dissertation concludes with a detail discussion of results, conclusions and the broad impacts in the relevant research fields in chapter 5.

2.0 PROJECT PORTFOLIO SELECTION TO IMPLEMENT LEAN AND SIX SIGMA CONCEPTS

Sustainability in the manufacturing industry is one of the essential elements in the achievement of the goal for sustainable society development. In the past 50 years, many manufacturing companies have taken steps to improve the production efficiency and quality. Many initiatives of lean production and manufacturing have emerged during this process.

Lean and Six Sigma methodologies play an important role in the quality and cost driven world with high level of competition in the manufacturing industry. With the increasingly competitive landscape, rapid and significant productivity improvement is becoming a requirement for company survival. Six Sigma tools and techniques, together with methodologies of the lean practice, have enabled productivity growth and efficiency improvement in the manufacturing sector. The integration of Lean and Six Sigma concepts have been claimed to provide the basis for the strong complementary relationship between process, quality, and performance that leads to sustainable competitive advantages for companies [32]. Lean and Six Sigma are also believed to be the realistic method for rapidly improving enterprise performance in a cost-effective, efficient, and timely manner.

In this study, we develop a unique decision support system that utilizes a multi-objective formulation for project portfolio selection problem in manufacturing companies. The model can be used to effectively implement Lean and Six Sigma concepts. An industrial case study that utilizes this model for implementing the Lean and Six Sigma initiatives is also presented in this chapter.

2.1 INTRODUCTION

The concept of implementing Six Sigma in manufacturing companies was first introduced at Motorola in the 1980s and the objective of that initiative was to reduce the number of production defects to as low as 3.4 parts per million opportunities [33]. Since then, Lean and Six Sigma have been recognized among the most significant threads of development in technology, quality and measurement domain [34]. Lean and Six Sigma enable companies to better identify and meet customer needs. In addition, Lean and Six Sigma emphasize continuous improvements, where performance is constantly evaluated with the objective of improving the process [35].

Although proper implementation of Lean and Six Sigma concepts can lead to breakthrough in product profitability and quality improvement, the successful application of these concepts in manufacturing companies is not an easy and quick process. According to the Aberdeen Group in 2006 [36], "Industry is missing out billions of dollars in potential savings, sales, and profits each year through the ineffective application of Six Sigma tools and methodologies."

In the Lean and Six Sigma implementation process, project selection problem has been recognized as one of the most important factors in the corporate decision making. How companies identify, prioritize and approve projects within the framework of their Lean and Six Sigma programs can determine the success of implementation to a large extent.

In this study, we develop a unique decision support system that utilizes a multi-objective model for project portfolio selection problem in manufacturing companies. The model can be used to effectively implement Lean and Six Sigma concepts in manufacturing companies. An industrial case study that utilizes this model for implementing the Lean and Six Sigma initiatives is also presented to validate the model. This model also has the flexibility of being extended to various industrial applications.

The remainder of this chapter is organized as follows: a literature review is presented in section 2.2; the multi-objective project selection model formulation is introduced in section 2.3, which includes a detailed scenario description, methodology introduction, objective functions, constraints and solution techniques; in section 2.4, an industrial case study is then presented to validate the model formulation. This chapter concludes with summaries and managerial suggestions in section 2.5.

2.2 LITERATURE REVIEW

Lean and Six Sigma as a quality improvement framework have gained increasing attention in both academia and industry in the recent years. These concepts have been acknowledged as an effective quality methodology and approach that can dramatically improve the performance of business organizations. Despite successful Lean and Six Sigma applications in various sectors, this approach has been criticized as not being easy to implement and requiring much human intervention [37]. Therefore, the implementation of Lean and Six Sigma concepts will directly affect the performance of the initiatives.

In initiating a Lean and Six Sigma framework, the first step is usually to solicit improvement suggestions from company personnel and management. In addition, it often takes large amounts of time and effort to adopt and realize these Lean and Six Sigma concepts in manufacturing companies [38,39]. The lack of quantitative support for corporate decision making has led to confusion and even failure in the Lean and Six Sigma implementation process. In the implementation process, the project selection process is believed to be one of the complex elements by corporate executives.

Most of the existing research related to the Lean and Six Sigma implementation is qualitative in nature. Pavnaskar et al. [40] study the classification scheme for lean manufacturing tools which can better help companies to implement the Lean and Six Sigma concepts. Snee and Rodebaugh [41], at the conceptual level, discuss the four key phases of the project portfolio selection and portfolio management process. Mckay [42] conducted a survey on manufacturing control practices from a production research perspective. Goh [43] completed a strategic assessment of Lean and Six Sigma concepts which is also qualitative oriented. Coronado and Antony [44], in their paper, discuss the critical factors for successful implementation of Six Sigma project in organizations, which include management involvement, cultural change, communication, training and organizational infrastructures.

Banuelas and Antony [45] examine the differences and similarities of Six Sigma improvement methodology and the approach of Design for Six Sigma (DFSS). However, managerial aspects are their primary focus in the paper. Amheiter and Maleyeff [46] study the integration effect of Six Sigma and lean management. The objective here is to eliminate misconceptions regarding Six Sigma and lean management by describing the key concepts and techniques that underlie the implementation process. According to Amheiter and Maleyeff, the benefits of Six Sigma and lean management, when undertaken individually, quickly reach a point of diminishing returns. This is due to that Six Sigma focus on the manufacturers' side (to achieve low production cost) and lean management focus on the consumers' side (to achieve high value for the consumers). However, when they are integrated into a common framework in project implementation, the benefits are leveraged as shown in Figure 3. This is one of the reasons why many companies are combining Lean and Six Sigma for implementation.

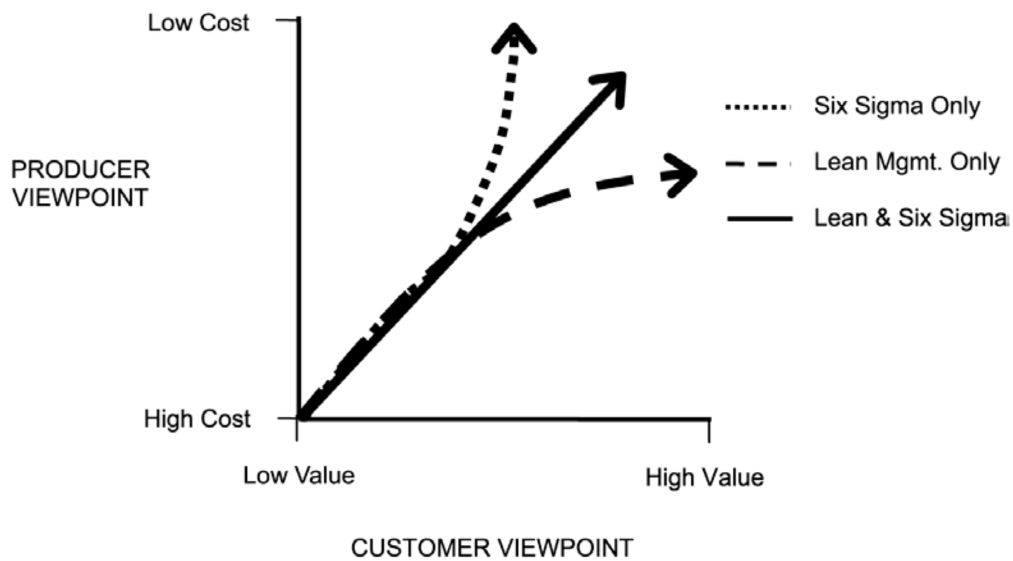

Figure 3. Comparison of Lean and Six Sigma Strategies [44]

From a project selection research perspective, the majority of published literature relates to R&D project selection area. A common approach in R&D project selection [47, 48] is quantifying the technical and commercial successes by probabilities and the benefits if successfully implemented. An overall expected value/score is obtained by multiplying the probabilities and benefits, and utilized for decision making. Steward [49] discusses a multi-criteria decision support system for R&D project selection carried out for large electricity utility corporations. He proposes a non-linear knapsack problem and the problem can only be solved by a heuristic algorithm. Bidanda and Cleland [50] study techniques that can help decision makers evaluate the profitability of projects as influenced by the length of the projects' lifecycle. Ringuest and Graves [51,52] propose a project selection criterion of cash flow over time instead of the prevailing criterion of net present value approach in the context of R&D project selection. Stummer and Heidenberger [53] extend this criterion to multiple objectives by integrating all relevant benefits together. However, from a mathematical point of view, it is still a single objective model formulation. Bordley [54] describes the experience and application of decision analytic project selection system in General Motors' R&D projects. He believes that the potential benefits of establishing the foundation for other better projects should also be considered. This was one of the motivating factors in considering interactions between projects in this study. It must be noted, however, that implementing Lean and Six Sigma concepts is not a typical R&D project due to its strong application orientation.

This study considers the problem of identifying a project portfolio in order to implement the Lean and Six Sigma concepts. Given a group of project proposals, the process of identification of a subset from the group in order to achieve the multiple objectives efficiently is a critical decision for many manufacturing companies. Typically, decision makers pick a project portfolio based on their experience and subjective preferences. However, as the number of the available projects increases, decision making without quantitative support can carry significant risks. A multi-objective mathematical model is proposed to characterize this process and provide solution techniques that obtain an optimal project portfolio. This model provides a decision support tool for manufacturing companies to choose the "best" project combination for the Lean and Six Sigma improvement on their shop floor.

The main contribution of this study is the multi-objective formulation where the benefit objective function is novel and the weights of the multiple objectives can be flexibly determined by the corporate management team. The output is a Pareto frontier chart that allows decision makers to have the flexibility of choosing the optimal decision based on the specific focus which may change over time. In this Lean and Six Sigma application, corporate decision makers are concerned about both the benefits and the costs of project portfolio implementation.

2.3 MULTI-OBJECTIVE PROJECT SELECTION MODEL

2.3.1 Scenario Description

Consider the following case: A company is considering the implementation of the Lean and Six Sigma concepts. There are *N* project proposals to achieve the goal. These project proposals are solicited from various departments in the company. Each project can have different sub goals, budgets and resource consumption. Each project has one project manager and belongs to one pre-specified category. The company has certain overall budget and other resource constraints, such as capacity, human resources, etc.

In order to implement the Lean and Six Sigma concepts successfully, the decision maker must choose a group of projects in order to minimize the investment as well as maximize the company benefits. In this context, company benefits translate into enhancing performance, productivity and profitability by alleviating defects, waste, lead time through improving product quality and reliability.

As we can see from the scenario description above, there is more than one objective (maximizing company benefits and minimizing the overall cost) in this problem. Therefore, a multi-objective model is formulated to solve the problem.

2.3.2 Multi-objective Programming Model

Multi-objective programming is a methodology which solves decision making problems where there are trade-offs between various objectives. It allows solving problems with multiple objectives by assessing the tradeoffs between the solutions.

Multi-objective Programming Background:

Francis Y. Edgeworth and Vilfredo Pareto first introduced the concept of non-inferiority which was utilized in the context of economics [55]. Since then, multi-objective optimization has been very popular in the engineering and design area.

Multi-objective mathematical programming problem is often interpreted as assisting the decision makers to select values for each of *n* decision variable, $x = (x_1, x_2, \cdots, x_n)$ in order to optimize $p(p \geq 2)$ objective functions $f_1(x), f_2(x), \cdots f_p(x)$ [56].

Without loss of generality, maximization can be used to express the optimization since minimization can be converted to maximization by multiplying the objective function by -1. Mathematically, the multi-objective programming can be denoted as:

$$\text{Maximization} \quad f(x) = [f_1(x), f_2(x), \cdots f_p(x)] \text{ subject to } x \in X$$

Ideally, we want a solution $x = (x_1, x_2, \cdots, x_n)$ which maximizes each of the objective functions simultaneously. We call this kind of solution a superior solution.

Definition of superior solution: A solution x^* is said to be superior if and only if $x^* \in X$, and $f(x^*) \geq f_i(x)$ for all $x \in X$.

However, in real life, superior solution seldom exists. In most cases, the multiple objectives are conflicting in nature, for example, lower the cost of implementing a project will usually lead to less satisfactory outcome. Therefore, the decision makers are often more interested in finding efficient solutions for the multi-objective problem.

Definition of efficient solution: A solution x^* is said to be efficient: (1) $x^* \in X$, x^* is feasible; (2) there does not exist other feasible solution *x*, such that $f(x^*) \leq f_i(x)$ for all $i = 1,2,\cdots p$ and $f(x^*) < f_i(x)$ for some $i = 1,2,\cdots p$.

In other words, an efficient solution is one for which there does not exist another feasible solution that is at least as good on every single objective function and better on at least one objective function. Typically, there exists a set of such efficient solutions which researchers call it Pareto optimality set or Pareto frontier.

Computationally, it is infeasible to obtain every single point in the Pareto frontier set. Therefore, researchers usually integrate the multiple objective functions into one and solve it using linear programming or nonlinear programming depending on the feature of the objective function [57]. The most common approach to integrate these objective functions is by assigning weights to each of them.

Another method to solving multi-objective programming is goal programming [58]. Goal programming bears the simple idea that the line between objectives and constraints is not completely solid. For the multi-objective problem, goal programming treats some of the objective functions as constraints.

In this study, a goal programming approach is adopted. However, instead of integrating multiple objectives into one, which is traditionally utilized to solve multi-objective problem, a Pareto optimal frontier chart is derived. This Pareto optimal frontier chart has property of capturing the features of all the possible optimal solution. In addition, this allows the decision makers to have the flexibility to pick the specific project portfolio based on the weights of different objectives.

Multiple Objective Functions:

In the context of the Lean and Six Sigma implementation, the two objectives being considered in this study are the maximization of the overall company benefits and the minimization of the total cost of the project portfolio.

- **Minimization of implementation costs:**

Here, overall cost of the project portfolio is just a simple summation of the cost for each project which has been chosen in the portfolio.

$$\text{Min} \quad C(x_1, x_2, \cdots, x_N) = \sum_{i=1}^{N} c_i x_i \tag{2-1}$$

$C(x_1, x_2, \cdots, x_N)$ is the overall cost of the project portfolio, where c_i is the cost of the *i*th project. x_i's are binary variables, if $x_i = 1$ then the *i*th project is selected; if not, then $x_i = 0$.

- **Maximization of the benefits:**

In order to maximize the potential benefits from implementation of the project portfolio, it may be necessary to go beyond the simple summation of the utility or benefit from each project chosen (as is traditionally modeled in literature). Interactions may exist among projects during implementation. Therefore, a novel type of objective function is proposed to characterize the overall integrated benefit, we call it $B(x_1, x_2, \cdots, x_N)$.

The objective is to maximize the benefit function:

$$\text{Max } B(x_1, x_2, \cdots, x_N) = \sum_{j=1}^{M} w_j \left[1 - \prod_{i=1}^{N} (1 - s_{ij})^{x_i} \right] \quad (2\text{-}2)$$

Where s_{ij} is the normalized performance score for the *j*th Lean and Six Sigma sub goal of the *i*th project proposal, and w_j is the weight of the *j*th sub goal in the achievement of the ultimate goal which is determined by the management decision making group. The normalized performance score s_{ij} is calculated from the project evaluation data from the corporate management group.

$$s_{ij} = \frac{\text{Performance evaluation score}}{\text{Highest performance evaluation score in the category} + 1} \quad (2\text{-}3)$$

As we can see, the higher s_{ij} is, the more benefit project *i* can bring for the achievement of Lean and Six Sigma sub goal *j*. Since the performance score >0, $0 < s_{ij} < 1$.

The concept of probability of the parallel systems in probability theory is adopted and the integrated performance score for the *j*th Lean and Six Sigma sub goal of the chosen project portfolio is $1 - \prod_{i=1}^{N} (1 - s_{ij})^{x_i}$. Therefore, the integrated benefit function is derived by incorporating the weights and the benefits from each Lean and Six Sigma sub goal.

As we can see, $1-\prod_{i=1}^{N}(1-s_{ij})^{x_i}$ is highly nonlinear, and it becomes computationally infeasible to solve this nonlinear integer programming model when N increases. Therefore, simplifications are applied to make it computationally approachable.

Max $B(x_1, x_2, \cdots, x_N) = \sum_{j=1}^{M} w_j \left[1-\prod_{i=1}^{N}(1-s_{ij})^{x_i} \right]$ is equivalent to:

Min $B^{'}(x_1, x_2, \cdots, x_N) = \sum_{j=1}^{M} w_j \prod_{i=1}^{N}(1-s_{ij})^{x_i}$, since $\sum_{j=1}^{M} w_j = 1$ is a constant.

To further simplify the function, a logarithmic summation is used instead of the exponential product. And the benefit objective function becomes:

$$\text{Min } B^{''}(x_1, x_2, \cdots, x_N) = \sum_{j=1}^{M} w_j \sum_{i=1}^{N} x_i \lg(1-s_{ij}) \tag{2-4}$$

We define $B^{''}(x_1, x_2, \cdots, x_N) = \sum_{j=1}^{M} w_j \sum_{i=1}^{N} x_i \lg(1-s_{ij})$ as the benefit index for the project portfolio. The smaller the benefit index, the larger potential benefit will be gained from the implementation of the project portfolio.

By these equivalent transformations, we derive a linear benefit objective function which becomes computationally solvable.

Model Constraints:

The objective functions introduced above are subject to several groups of constraints which are motivated both from the literature study and by communication with corporate management group:

- **Resource Constraints:**

Each company has limits on its available resource. For example, Lean and Six Sigma projects are typically led by "black belts". The number of projects a company can implement may be limited by the number of "black belts" at the company and their time constraints. Therefore, resource constraints are included in the model.

$$\sum_{i=1}^{N} r_{ij} x_i \le R_j ;\ j \in J , \qquad (2\text{-}5)$$

where r_{ij} is the resource requirement for the *j*th resource by *i*th project, R_j is the limit for *j*th resource and *J* is the set of critical resource, such as facility capacity, labor resource, and so on.

- **Diversity Constraints:**

In undertaking a company-wide Lean and Six Sigma initiative, it is necessary to involve all stakeholders, even though some units (and associated projects) may not carry large potential benefits. A Lean and Six Sigma mission is generally the integration of various aspects for waste reduction and quality improvement.

Therefore diversity constraints are included because the decision makers do not always want to choose all projects in the same Lean and Six Sigma implementation category (i.e., the project portfolio should ideally encompass as broad a spectrum as feasible within the company):

$$\sum_{i \in C_k} x_i \le K_k \, , \tag{2-6}$$

where C_k is the set of projects in *k*th category and K_k's are prespecified constants.

- **Management Constraints:**

Management constraints address the issue that limits exist on the number of projects that a management group is responsible for.

$$\sum_{i \in PM_p} x_i \le P_p \, , \tag{2-7}$$

where PM_p is the set of projects which will be managed by *p*th management group and P_p's are prespecified constants.

2.3.3 Model Summary and Solution Techniques

In this section, the multi-objective model formulation is summarized and solution techniques are introduced.

Model Summary:

This Lean and Six Sigma project portfolio selection problem is formulated as a multi-objective integer programming model with linear objectives and linear constraints:

$$\text{Min } C(x_1, x_2, \cdots, x_N) = \sum_{i=1}^{N} c_i x_i \tag{2-8}$$

$$\text{Min } B''(x_1, x_2, \cdots, x_N) = \sum_{j=1}^{M} w_j \sum_{i=1}^{N} x_i \lg(1 - s_{ij}) \tag{2-9}$$

s.t.

$$\sum_{i=1}^{N} r_{ij} x_i \le R_j ;\ j \in J \quad \text{(Resource Constraints)} \tag{2-10}$$

$$\sum_{i \in C_k} x_i \le K_k \quad \text{(Diversity Constraints)} \tag{2-11}$$

$$\sum_{i \in PM_p} x_i \le P_p \quad \text{(Management Constraints)} \tag{2-12}$$

Solution Techniques:

Matlab™ and Cplex™ were used to solve the integer programming and detailed analysis is included in the following industrial case study section.

2.4 INDUSTRIAL CASE STUDY

We now present a validation of the multi-objective project portfolio selection model by its application at a mid-sized manufacturing organization in the power semi-conductor sector.

Currently, corporate management makes decisions based on the experiences and subjective preferences. Scores are assigned and ranked for each project. Projects are selected sequentially based on the scores till the budget limit is reached. The major limitation is that there are some criteria that cannot be characterized into the overall score.

After discussion with the management team, three broad constraints for implementation were identified. These include: the diversity, human resource and management coordination issues. Even if the score system is accurate enough to comprehensively characterize the project features, this simple scoring and ranking project selection mechanism may not provide the “best” choice for the decision maker.

2.4.1 Preliminary Data Analysis

In this case study, the corporate management received 51 project proposals. The overall available budget to implement the Lean and Six Sigma concepts was $1,500,000. However, investment minimization and potential company benefits maximization are the two primary objectives of this project selection problem.

Table 1 details the information of the project proposals, including the project expense, potential benefit index, Lean and Six Sigma category. Depending on their primary objective, the project proposals are categorized into six groups as follows:

- Cost Reduction, whose main objective is to reduce cost;
- Replacement, which aims at replacing old, dated or inefficient machines;
- Productivity, which focuses on improving productivities;
- Capacity, in which they rearrange the capacity setup;
- Yield, which concentrate on the objective of yield improvement;
- New Product, which focuses on developing new products.

The potential benefit index for a single project is defined as $BI(x_i) = \sum_{j=1}^{M} w_j \lg(1 - s_{ij})$, in which w_j and s_{ij} were determined by the corporate management group discussion and brainstorming. For example, for project 1, its benefit index is $BI(x_1) = \sum_{j=1}^{9} w_j \lg(1 - s_{1j}) = -11.9251$.

Table 1. Project Proposal Information

Project Number	Expense	Benefit Index	Lean and Six Sigma Category	Engineer Group Number
1	$30,000	-11.9251	Cost Reduction	1
2	$40,000	-6.9599	Replacement	1
3	$10,000	-19.2145	Cost Reduction	1
4	$10,000	-8.1496	Productivity	1
5	$24,000	-11.2081	Replacement	1
6	$80,000	-11.5242	Replacement	1
7	$10,000	-5.6630	Productivity	1
8	$25,000	-9.6803	Capacity	1
9	$15,000	-13.5515	Yield	1
10	$2,500	-11.8776	Yield	1
11	$12,000	-9.3927	Productivity	1
12	$60,000	-9.9396	Capacity	1
13	$10,000	-9.3878	capacity	1
14	$150,000	-11.0097	Cost Reduction	1
15	$26,000	-9.1001	Replacement	2
16	$35,000	-8.4118	New Product	2
17	$15,000	-7.4831	Yield	2
18	$100,000	-10.6612	Replacement	2
19	$160,000	-20.3131	Yield	2
20	$4,000	-16.7296	Productivity	2
21	$45,000	-9.9917	Yield	2
22	$20,000	-12.4529	Replacement	2
23	$70,000	-12.5944	Capacity	3
24	$8,000	-8.9351	Productivity	3

Table 1 (continued)

25	$23,050	-18.6391	Productivity	3
26	$3,500	-13.2639	Productivity	3
27	$27,000	-12.1083	Productivity	3
28	$2,500	-13.6693	Productivity	3
29	$20,000	-15.8903	New Product	3
30	$4,000	-16.5597	Yield	3
31	$12,000	-10.8311	Productivity	3
32	$100,000	-12.9762	Replacement	4
33	$20,000	-18.2337	Replacement	4
34	$10,000	-12.8584	Replacement	4
35	$10,000	-10.9489	New Product	4
36	$5,000	-14.2447	Productivity	4
37	$130,000	-7.4784	Replacement	4
38	$50,000	-12.3959	Productivity	4
39	$18,000	-13.1461	Replacement	5
40	$60,200	-12.3351	Replacement	5
41	$205,000	-10.8967	Replacement	5
42	$50,000	-3.4912	Replacement	5
43	$82,000	-4.4466	Replacement	5
44	$6,000	-10.9205	Replacement	5
45	$40,000	-15.0556	Replacement	5
46	$100,000	-6.7900	Replacement	5
47	$3,500	-6.3796	Replacement	5
48	$10,000	-4.0932	Replacement	5
49	$7,000	-5.3096	Yield	5
50	$20,000	-13.1461	Cost Reduction	6

Table 1 (continued)

51	$40,000	-12.1653	New Product	5

Figure 4 gives a more straightforward presentation of the relationship between a single project cost and the potential benefit index (the less, the better). The x-axis is the expense for a single project and the y-axis the potential benefit index (the less, the better) of the project.

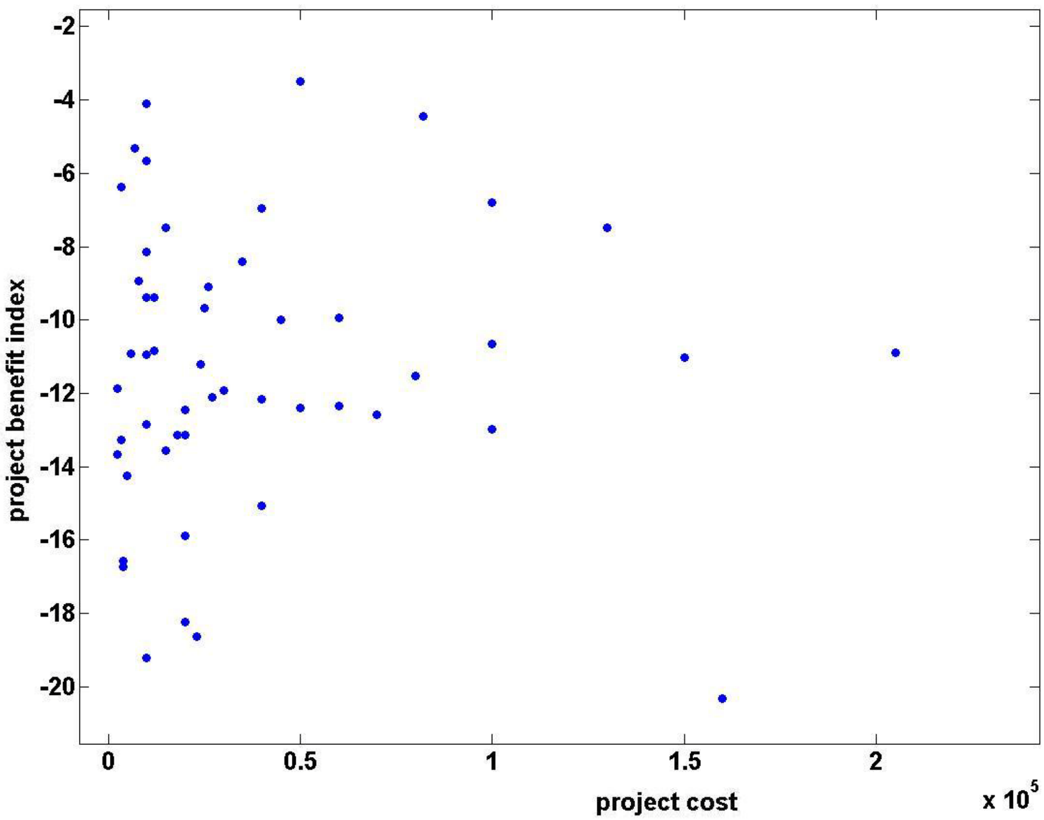

Figure 4. Single Project Cost ($) vs. Benefit Index

Intuitively, projects that are in the bottom left quadrant are the most effective projects since they have low costs and high potential benefits (low benefit indices). On the other hand, projects that are in the upper right quadrant are the least effective projects since they have higher costs and low potential benefits (high benefit indices).

Therefore, the project proposals can be roughly categorized into 4 regions: high potential projects (with low cost and high potential benefits), low potential projects (with high cost and low potential benefits) and two neutral project regions (either with low cost and low potential benefits or with high cost and high potential benefits). Figure 5 shows the categories for the project proposals.

High Benefit Index	Neutral; Constraints play a critical role	Low Potential Projects
Low Benefit Index	High Potential Projects	Neutral; Constraints play a critical role
	Low Cost	High Cost

Figure 5. Categories for Project Proposals

2.4.2 Numerical Results and Analysis

In order to identify the optimal project portfolio to implement the Lean and Six Sigma concepts, the multi-objective mathematical model introduced in section 2.3 is utilized to approach the problem.

Since there are 51 project proposals, there are 2^{51} possible choices of the project portfolio. We picked the top 100 portfolios which are shown in Pareto frontier chart in Figure 6.

The top 100 portfolios are obtained by setting the project portfolio budget at 100 different levels and solving the integer program model summarized in section 2.3.3. Each point on the frontier represents a candidate the optimal project portfolio. Final optimal project portfolio is picked depending on the priority determined by the decision maker. The two axes denote the two objectives being considered: the project portfolio cost and the integrated portfolio benefit index (the less, the better).

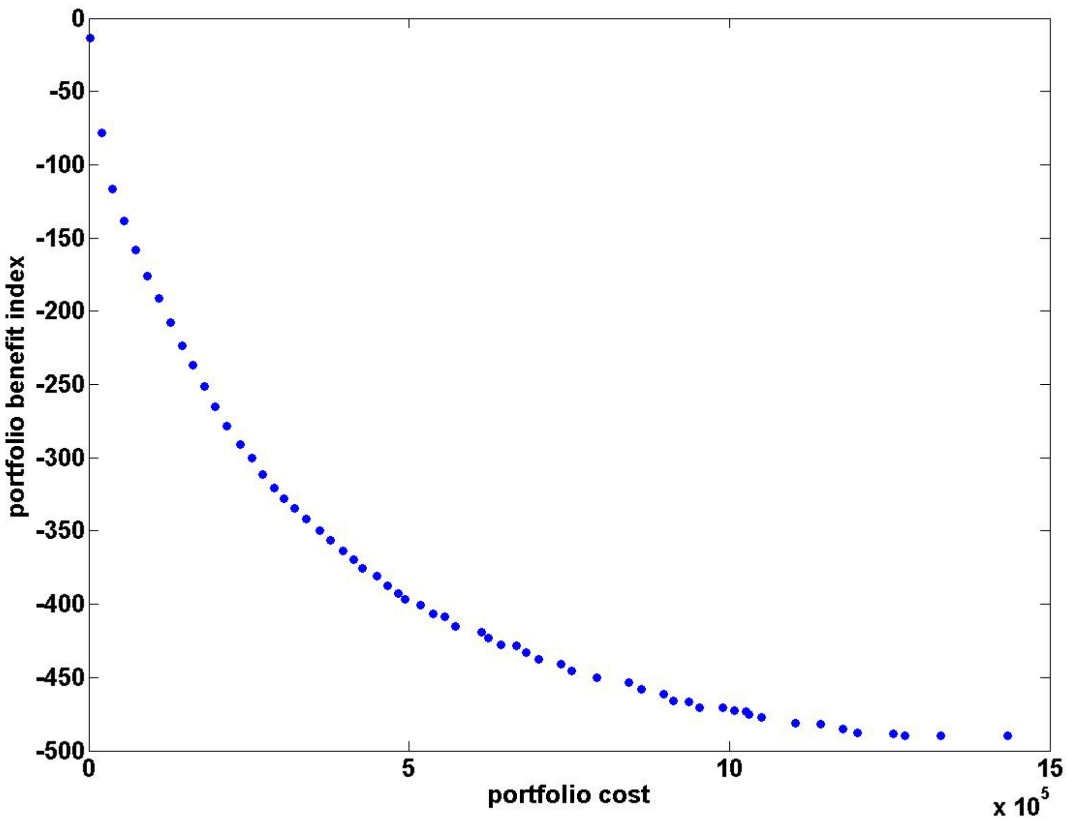

Figure 6. Pareto Frontiers of Project Portfolio Cost ($) vs. Benefit Index

In order to further analyze the relationship between the optimal portfolio sets and the individual projects, we compare the frequencies of projects chosen in the Pareto frontier set. Figure 7 is the 3-D histogram of the project chosen frequencies. The x-axis is the cost of each project, y-axis is the corresponding benefit index and z-axis is the histogram of project chosen in the Pareto frontier set. One interesting finding is that the optimal choice is more sensitive to the cost than to the benefit index, since the heights of the line don't change significantly with the change of the benefit index. On the other hand, they decrease dramatically with the increase of the project cost.

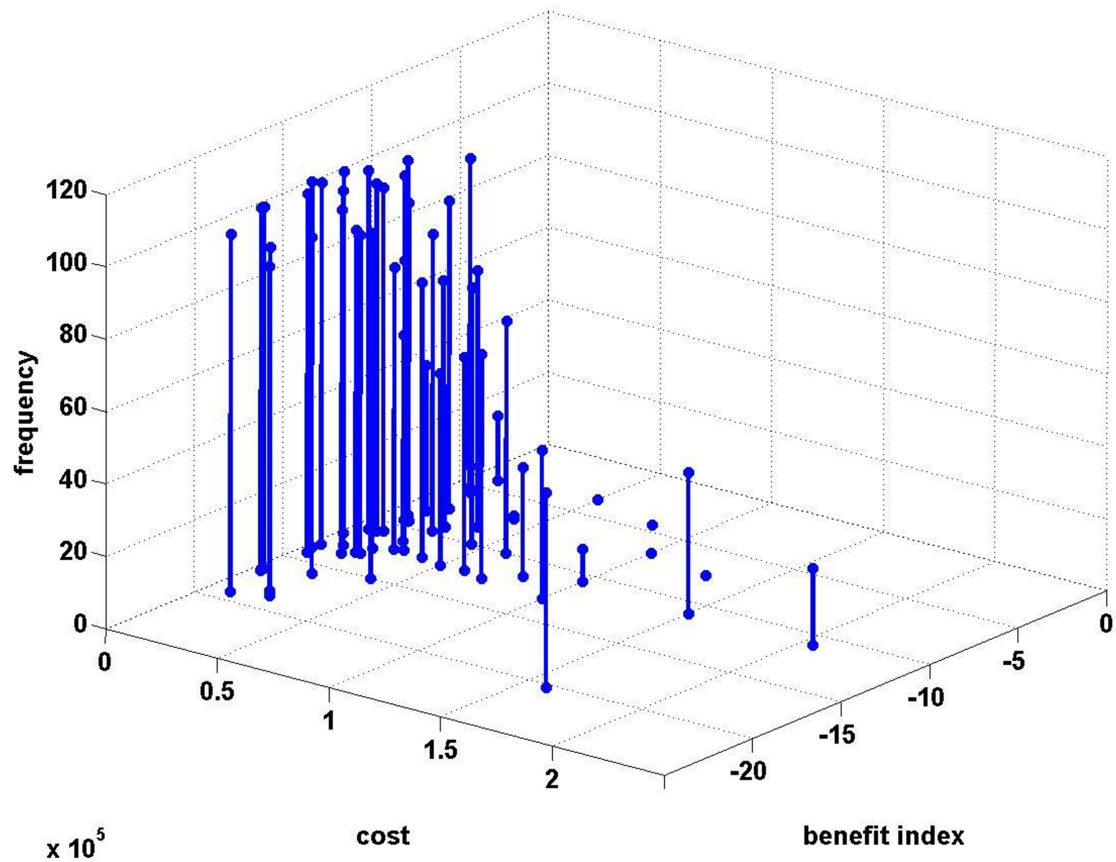

Figure 7. Histogram of Projects Chosen in the Pareto Frontier

Figure 8 further demonstrates the frequencies of potential projects chosen in the Pareto frontier portfolios. It is a re-plot from figure 4 with additional information about the project selection frequency. The x-axis is the cost of each project and the y-axis is the benefit index. This size of solid shape (either round or square) denotes how frequently the project has been chosen. The larger the size is, the more frequently it has been picked in Pareto frontier portfolio set.

In addition, figure 8 differentiates between the projects that have never been chosen in any other Pareto optimal portfolio in the frontier set and the specific project portfolio when the cost reaches the budget limit of $1,500,000. The hollow square data points which are in the top right quadrant are those never chosen in any Pareto frontier portfolio and the solid square data points are those not chosen in the $1,500,000 budget optimal portfolio but are chosen in some other optimal portfolios in the Pareto frontier set. This frequency graph shows the consistency with the categories in Figure 5, where project candidates can be roughly categorized into 4 regions.

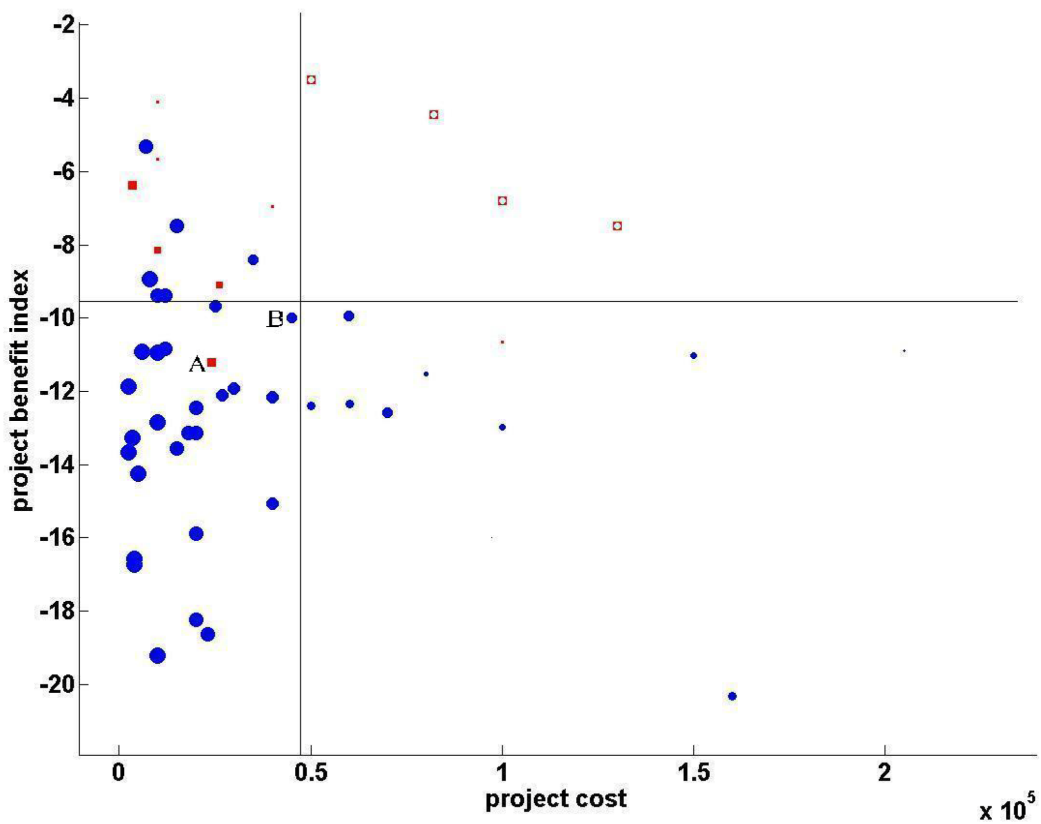

Figure 8. Project Cost ($) vs. Benefit Index

Another observation is that the frequencies are not monotonically decreasing with the increase of the cost or the decrease of the potential benefit (the increase of the benefit index). The explanation is that the diversity and management limit constraints exclude these simple monotonic properties. From another perspective, this is one advantage of this multi-objective model decision support system over current decision systems utilized by the corporate executives.

This non-monotonic phenomenon illustrates that simple potential and benefit dominations do not lead to absolute preference in the selection process. For example, in the $ 1,500,000 budget case, as denoted in figure 8, project B is dominated by project A, however, the optimal portfolio selects project B instead of A. This is often due to additional constraints in the model.

To analyze the frequencies of the projects selected in the Pareto frontier set, we present the frequency comparisons in table 2, which is a rearrangement of table 1. The benefit/cost ratio in table 2 is defined as $\frac{|\text{Project Benfit Index}|\times 10000}{\text{Project Expense}}$.

In table 2, rows are ranked by the frequencies for the Pareto frontier set. Intuitively, benefit/cost ratio should also monotonically increase. However, this is not the case shown in table 2. The most obvious outlier is the row of Index 19 (in bold and italic font) to distinguish it from other projects: the benefit/cost ratio is very favorable but the corresponding frequency is quite low considering the benefit/cost ratio. This inconsistency is counter-intuitive and probably due to the category balance and the management group limit constraints in the model.

Further, as shown in table 2, the shaded projects are those chosen in the $1,500,000 budget level. Although benefit/cost ratios appear favorable, projects 15 and 4 are not chosen. The reason for not choosing project 15 is that it is in Lean and Six Sigma category 2 and there are already enough projects chosen in that category which exclude its opportunity, while the rationale for excluding project 4 is similar to project 15, although the critical constraint in this case is at the management group aspect.

Table 2. Project Selection Frequency Comparison

Index	**Project number**	**Frequency**	**Benefit / Cost**	**Project Category**	**Management Group Number**
1	37	0	0.5753	Replacement	4
2	42	0	0.6982	Replacement	5
3	43	0	0.5423	Replacement	5
4	46	0	0.679	Replacement	5
5	2	1	1.74	Replacement	1
6	7	7	5.663	Productivity	1
7	18	9	1.0661	Replacement	2
8	48	18	4.0932	Replacement	5
9	41	21	0.5315	Replacement	5
10	6	30	1.4405	Replacement	1
11	15	38	3.5	Replacement	2
12	14	39	0.734	Cost Reduction	1
13	4	40	8.1496	Productivity	1
14	32	41	1.2976	Replacement	4
15	38	53	2.4792	Productivity	4
16	19	54	1.2696	Yield	2
17	5	57	4.6701	Replacement	1
18	40	59	2.049	Replacement	5
19	***47***	***59***	***18.2275***	***Replacement***	***5***
20	23	62	1.7992	Capacity	3

Table 2 (continued)

21	12	64	1.6566	Capacity	1
22	16	71	2.4034	Transition	2
23	21	71	2.2204	Yield	2
24	51	76	3.0413	Transition	5
25	27	78	4.4845	Productivity	3
26	45	78	3.7639	Replacement	5
27	1	80	3.975	Cost Reduction	1
28	8	82	3.8721	Capacity	1
29	17	85	4.9887	Yield	2
30	22	87	6.2265	Replacement	2
31	11	88	7.8272	Productivity	1
32	50	88	6.573	Cost Reduction	6
33	39	89	7.3034	Replacement	5
34	25	91	8.0864	Productivity	3
35	49	91	7.5852	Yield	5
36	29	93	7.9451	New Product	3
37	9	95	9.0344	Yield	1
38	13	95	9.3878	Capacity	1
39	31	95	9.0259	Productivity	3
40	33	95	9.1168	Replacement	4
41	35	96	10.9489	Transition	4
42	24	98	11.1689	Productivity	3
43	34	98	12.8584	Replacement	4
44	3	99	19.2145	Cost Reduction	1
45	36	99	28.4894	Productivity	4
46	44	99	18.2008	Replacement	5

Table 2 (continued)

47	10	100	47.5103	Yield	1
48	20	100	41.824	Productivity	2
49	26	100	37.8968	Productivity	3
50	30	100	41.3992	Yield	3
51	28	100	54.6773	Productivity	3

To best demonstrate the comparison between the current "rank and pick" method and the new decision model output, the overall cost and benefit for the portfolios are compared.

Table 3. Project Portfolio Comparison

	Overall Cost for Project Implementation	Company benefit	Satisfy Constraints or not?
Rank and Pick method	$1,453,250	541.3272	No
Multi-objective model	$1,434,750	490	Yes

As we can see, the current "rank and pick" method consumes more budget and generate more company benefit, while the new multi-objective model method consumes less budget and less benefits to the company. However, the new method help the company find the best project portfolio within budget and various constraints. This is the one of the major advantage of this multi-objective project selection model. This method has been validated by focused group study with company management team.

In order to investigate the process of the projects entering and leaving the optimal portfolio as the budget increases, the marginal benefit increases are investigated as the budget increases for the whole project portfolio. As shown in figure 9, the marginal benefit decreases as the budget increases. Therefore, as the company increases the total budget, the additional benefit per unit investment is decreasing.

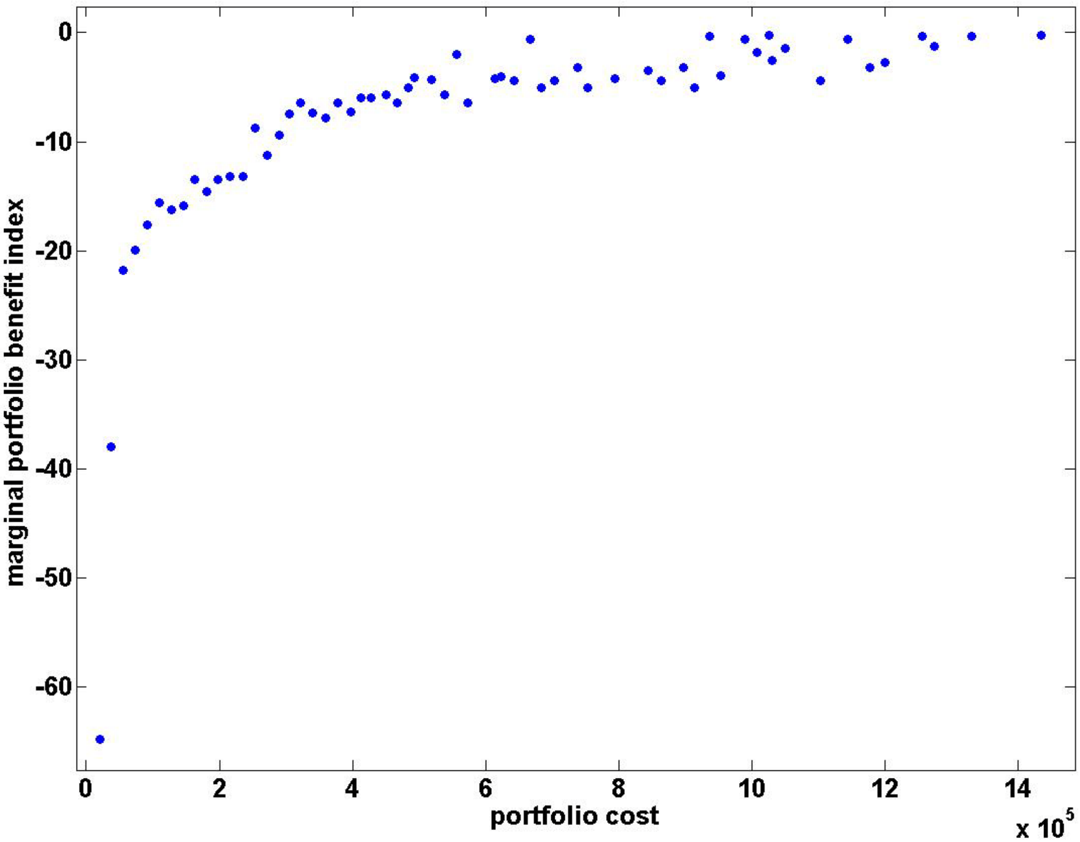

Figure 9. Project Portfolio Cost vs. Marginal Benefit Index

2.5 CONCLUSIONS

This part of the dissertation study considers a project portfolio selection problem in order to implement the Lean and Six Sigma concepts. A Multi-objective model is formulated to approach the problem and Pareto frontier chart is developed to assist decision makers. The industrial case study validates this decision support system.

The major findings are summarized as follows:

1. It is appropriate to utilize a multi-objective formulation to effectively solve the project portfolio selection problem in the Lean and Six Sigma implementation process. This can be used to provide quantitative support to the corporate executives when they make the decisions on project portfolio selection.

2. A decision support system based on the multi-objective mathematical model provides the flexibility of adjusting the weight of multiple objectives in the decision making process due to the property of Pareto frontier set.

3. The probability of choosing a project does not monotonically decrease with the increase in the project implementation cost and decrease in the potential benefit from the project. This is due to the additional constraints included in the realistic model formulation, such as diversity constraints and management limit constraints.

4. The integrated benefit objective function considers the interaction between projects in the process of implementation. The concept of probability of parallel systems can be adopted to address this issue.

5. It is necessary and appropriate to simplify the objective function for the overall benefits for project portfolio implementation. This makes the model computationally solvable.

In summary, this multi-objective decision-making model can provide assistance to corporate executives to identify the optimal project portfolio flexibly for Lean and Six Sigma deployment. In addition, this decision support system has the flexibility of being applied to other portfolio selection problems.

The major contribution of this study is objective function formulation. In the multi-objective model formulation, a novel way of defining the objective function for integrated benefit is developed. In addition, the simplification of the objective function for integrated benefit makes the mathematical programming solvable. This model formulation provides a new and better mechanism for project portfolio selection.

3.0 GAME THEORETICAL MODELS FOR MARKET COMPETITION ANALYSIS IN GREEN PRODUCTION

As global awareness and concern about the environment issues increase, many governments, various regulatory organizations and business leaders have begun to call on the business community to play a major role in the process of moving the global economy toward sustainability [59]. However, fierce market competition and price sensitivity have been big obstacles in the development of green production industry.

In this study, two groups of ordinary and green production sectors (either different companies or separate departments within the same company) produce a similar type of product with different materials and techniques. We categorize them as green and ordinary companies/production departments. Game theoretic models are formulated to analyze their competition in the market, and obtain the dynamic equilibrium under the free entry assumption. Sensitivity analysis and numerical examples can provide suggestions that help policy makers, government, company executives and customers to make rational decisions.

3.1 INTRODUCTION

The concept of “sustainability” was first introduced in the Brundtland Report of the UN World Commission on Environment and Development in 1987 [60]. In the Brundtland Report, “sustainability” is defined as “meeting the needs of the present without compromising the ability of future generations to meet their needs.” This definition includes both environmental and social goals, in which it claims that long-term environmental protection requires appropriate economic development.

At the same time, people in both academia and industry start to realize that there exists an intrinsic business value in the sustainability practices and it is growing as more and more consumers know about the importance of sustainable societal development. Sustainable products often refers to those products “providing environmental, social and economic benefits while protecting public health, welfare, and environment over their full commercial cycle, from the extraction of raw materials to final disposition [61].” Sustainable manufacturing also encompass sustainable manufacturing process, not only the output of the process: sustainable products. The mathematical model developed in this part of my dissertation can be applied for both scenarios of the sustainable manufacturing process.

The objective of this part of the dissertation is to understand the environment related decisions facing firms and policy makers and how to help green products better survive in the market competition. This study can help them make better decisions to achieve the win-win situation from the whole societal perspective.

This study considers the market competition between green and ordinary production sectors from a quantitative point of view. Game theoretic models with Nash equilibrium are developed and analyzed. Managerial and business insights for policy maker and business leaders are derived from the analysis and computational results.

The remainder of the chapter is organized as follows: literature review of relevant studies is introduced in section 3.2; the game theoretical model is introduced in section 3.3, including the

Cournot model, derivation of dynamic equilibrium and sensitivity analysis of the model parameter; in section 3.4, numerical examples with managerial insights are discussed to demonstrate the approach. This game theoretical model is extended in section 3.5 by considering "hybrid" companies (companies which produce both green and ordinary products) with corresponding numerical examples introduced in section 3.6. Finally, this chapter concludes with suggestions to both business and government sectors in section 3.7.

3.2 LITERATURE REVIEW

There has been extensive research done in the area of green production and marketing, especially in the study of the market competition as environmental awareness increases in the public domain. In this scenario, consumer consumption decisions are made not only based on the utility of the products but also the rightness/goodness of consuming the products.

The trend is that more and more consumers start to realize the importance of incorporating environmental concerns into the consumption considerations. A recent market survey suggests that 52%-59% of private households in the United States would be willing to pay a price premium to buy electricity that was produced using renewable energy technology [62]. In addition, many power companies now produce green electricity not only for the purpose of marketing but also from a profitability perspective. This makes a good example for the win-win situation in sustainability trend. However, this is not always the case due to the high costs in green production and limited public awareness.

According to K. Nyborg, R. B. Howarth, K. A. Brekke [63], "moral motivations" can potentially influence the customers' consumption choices. They developed a game theoretical model to analyze a consumer's choice where a psychological perspective is also considered. They found that the permanent increase in green consumption and production may be achieved by imposing taxes or subsidy. However, taxes can take responsibility away from consumers which in turn tamper the effect of taxes.

Governments and regulatory organizations are also taking steps to achieve the goal of sustainable development. Two examples include green production subsidy and tax reduction imposed by the government. S. Bansal and S. Gangopadhyay [64] studies two types of policies (tax based policy and subsidy based policy) in the presence of consumers who are concerned about the environmental issues. The conclusion is that a uniform subsidy policy improves average environmental quality while a uniform tax policy makes the pollution problem worse.

Government intervention is an effective way to help green production survive and thrive. In 1997, 20% of the consumers used non-studded winter tires in the city of Oslo. After a temporary tax on the use of the studded tires by the government, the percentage increased to 80% [65]. In addition, winter insulation subsidies have been successfully applied in many states in the US to increase the energy efficiency of houses. Significant impacts have been seen from this government initiative to make residential building greener.

Chialin Chen [66] develops a quality-based model for analyzing the strategic and policy issues concerning the development of products with conflicting traditional and environmental attributes. R. H. Wiser and S. J. Pickle [67] studied the green electricity market by conducting market surveys in California (one of the four pioneer states that emphasize sustainable development). They conclude that customer education is critical in the green industry development process and the growth of the green market, in a large extent, relies on the public policies.

Simulation approaches are widely recognized as an effective methodology to study the green production research problem since the real data is often not available. M. Janssen and W. Jager [68] utilized this methodology to study the introduction process of green products to the market. In this study, both consumers and firms are simulated as agents. Their experiments illustrate that the flexibility of companies to introduce new technology has an important influence on consumers when the consumers change their consumption behavior.

Kleindorfer, Singhal and Wassenhove [69], in their paper, discuss the challenges of integrating environment, health and safety concerns into green product design. Furthermore, green operations management and closed-loop supply chains issues are addressed from a conceptual perspective.

Game theory has been one of the most popular methodologies in the study of market competition in the sustainability domain. K. Conrad [70] carried out a study on market implications of product differentiation when there exists an environmentally conscious consumer sector. A spatial duopoly model is utilized to determine how the phenomenon affects the prices and market shares. Research has also been carried out on game theoretical model application in food industry [71]. However, in general, little work has been done on dynamic equilibrium as companies/production sectors enter or leave the market. In addition, not enough research has been carried out as for how government or regulator can do to better help environmental friendly products to better survive and thrive in the competitive market.

In this chapter, game theoretical models are formulated to analyze the market competition between green and ordinary companies/production sectors. The purpose of this study is to develop a quantitative model to help decision makers (in various domains) to understand the market competition between green and ordinary production industry and how the green products can better survive in the fierce market competition. Game theory is a suitable methodology in the aspect. This is the major motivation to use game theory methodology for this part of the dissertation study.

3.3 MODEL (A) FORMULATION

3.3.1 The Cournot Model and the Nash Equilibrium

Suppose there are n companies that use ordinary materials and/or techniques, and m companies that use green techniques and/or materials in a competitive market. We call them green company and ordinary company, respectively. The competition among these companies is assumed to be Cournot, which means that the companies independently and simultaneously determine their supply quantities in order to maximize their own profits.

Notations:

q_i^O : the supply quantity by an ordinary company *i;*

q_j^G : the supply quantity by a green company *j;*

Q^O: the total supply of ordinary products in the market where $Q^O := \sum_{i=1}^{n} q_i^O$;

Q_{-i}^O: the total supply of ordinary products in the market excluding the supply from ordinary company *i* where $Q_{-i}^O = Q^O - q_i^O$;

Q^G : the total supply of ordinary and green products where $Q^G := \sum_{j=1}^{m} q_j^G$;

Q_{-j}^G: the total supply of green products in the market excluding the supply from green company *j* where $Q_{-j}^G = Q^G - q_j^G$;

c^O , c^G : unit production costs of ordinary and green products, respectively;

p^O , p^G : prices (price consumers consider when they make their consumption choices, including their conception of long-term consumption price and effect on the environment) of ordinary and green products, respectively;

ρ^O , ρ^G : cash prices (price consumers pay upfront when they make their purchases) of ordinary and green products, respectively.

Assumptions:

- All ordinary companies have the same unit production cost c^O, and all green companies have the same unit production cost c^G.
- Prices of the ordinary and green products are determined by the inverse demand functions:

$$p^O = a - b(Q^O + \theta Q^G) , \quad (3\text{-}1)$$

$$p^G = a - b(Q^G + \theta Q^O) . \quad (3\text{-}2)$$

- In the demand functions, a and b are positive constants, and θ is the substitution parameter. The constant a bears the meaning of the upper bound price (the price is so high that no one will choose to consume it). The constant b is the unit price decrease of the product. The substitution parameter θ usually lies between 0 and 1. If the ordinary and green products are highly substitutable, then the value of θ is close to 1; if these products are distinct and non-substitutable, then the value of θ is close to 0. A negative value of θ indicates the complementarity of the products.

- Price p consists of two components: the cash price ρ and the long-term consumption price λ. For example, ρ is the cash price of a light bulb on the price tag, while λ is the long-term electricity consumption price of the light bulb.
- Besides economical long-term consumption price paid by the consumer directly, environmental effect price could also be considered into λ. This is due to the fact that when consumers make their consumption choices, they may consider whether it is good or bad for the environment. The environmental effect price is paid by the whole society in the long run.
- Consumers are assumed to take both the cash price ρ and the long-term price λ into account in their purchasing behavior.

Model Formulation:

Given the supply quantities of the other ordinary companies Q_{-i}^{O} and supply quantities of green companies Q^{G} , the profit of an ordinary company *i* is $\pi_i^O(q_i^O;Q_{-i}^O,Q^G)$:

$$\begin{aligned}
&\pi_i^O(q_i^O;Q_{-i}^O,Q^G)\\
&=(\rho^O-c^O)q_i^O\\
&=(p^O-\lambda^O-c^O)q_i^O\\
&=\left[a-b\left(q_i^O+Q_{-i}^O+\theta Q^G\right)-\lambda^O-c^O\right]q_i^O\\
&=-b\left(q_i^O\right)^2+\left[a-b\left(Q_{-i}^O+\theta Q^G\right)-\lambda^O-c^O\right]q_i^O
\end{aligned} \tag{3-3}$$

As we cans see from the analysis above, $\pi_i^O(q_i^O; Q_{-i}^O, Q^G)$ is a concave quadratic function of its supply quantity q_i^O, therefore, the best response of the ordinary company *i* is:

$$\left(q_i^O\right)^* = \frac{a - b(Q_{-i}^O + \theta Q^G) - \lambda^O - c^O}{2b}. \tag{3-4}$$

Similarly, given the supply quantities of the other green companies Q_{-j}^G and supply quantities of ordinary companies Q^O, the profit of a green company *j* is $\pi_j^G(q_j^G; Q_{-j}^G, Q^O)$:

$$\begin{aligned}
&\pi_j^G(q_j^G; Q_{-j}^G, Q^O) \\
&= (\rho^G - c^G) q_j^G \\
&= (p^G - \lambda^G - c^G) q_j^G \\
&= \left[a - b\left(q_j^G + Q_{-j}^G + \theta Q^O\right) - \lambda^G - c^G\right] q_j^G \\
&= -b\left(q_j^G\right)^2 + \left[a - b\left(Q_{-j}^G + \theta Q_O\right) - \lambda^G - c^G\right] q_j^G
\end{aligned} \tag{3-5}$$

Similar as $\pi_i^O(q_i^O; Q_{-i}^O, Q^G)$, the profit of a green company *j* shown above. $\pi_j^G(q_j^G; Q_{-j}^G, Q^O)$ is also a concave quadratic function of its supply quantity q_j^G, therefore, the best response of the green company *j* is:

$$\left(q_j^G\right)^* = \frac{a - b(Q_{-j}^G + \theta Q^O) - \lambda^G - c^G}{2b}. \tag{3-6}$$

Taking summations of the best response of ordinary company *i* over *i* and the best response of green company *j* over *j*, respectively, we obtain the supply quantities of the companies under Nash equilibrium.

Since all ordinary and green companies are respectively symmetric, they will have the same supply quantities under equilibrium:

$$(q^O)^* = \frac{(m+1)(a - \lambda^O - c^O) - m\theta(a - \lambda^G - c^G)}{b[(n+1)(m+1) - nm\theta^2]}, \tag{3-7}$$

$$(Q^O)^* = n(q^O)^*, \tag{3-8}$$

$$(q^G)^* = \frac{(n+1)(a-\lambda^G - c^G) - n\theta(a-\lambda^O - c^O)}{b[(n+1)(m+1) - nm\theta^2]}, \tag{3-9}$$

$$(Q^G)^* = m(q^G)^*. \tag{3-10}$$

We assume that

$$(m+1)(a-\lambda^O - c^O) > m\theta(a-\lambda^G - c^G) \tag{3-11}$$

$$(n+1)(a-\lambda^G - c^G) > n\theta(a-\lambda^O - c^O) \tag{3-12}$$

to ensure that $(q^O)^* > 0$ and $(q^G)^* > 0$.

Assumption $(n+1)(a-\lambda^G - c^G) > n\theta(a-\lambda^O - c^O)$ provides the necessary conditions for green companies to emerge into the market and survive in the competition with ordinary companies.

Through detailed investigations, in order to ensure the necessary condition above, we need to:

(a) have a small value of θ, which means that green companies should sufficiently distinguish their products from the ordinary products and avoid becoming a simple substitution with the same design and function;

(b) to have a relatively small unit production cost c^G, which means that lower green production cost helps green companies to keep their market share in the competition.

In other words, a green company that produces an exact substitute of the ordinary product with substantially higher cost will be driven out of the market. On the other hand, green production with distinguished design and lower cost can survive and thrive in the market competition.

Engineering and Managerial Insights:

To distinguish its products from the ordinary ones, a green company could combine innovative design with the green techniques. For example, Toyota Prius has its unique appearance in addition to its hybrid functionality. Actually a large number of consumers choose to buy this brand just want to deliver a message that they are trendy and pioneer in the green consumption arena. Their objective is not only to save money by saving gasoline consumption but also to enjoy the psychological/mental happiness/benefit from driving Prius around.

In addition, to increase the public concern about the environmental issues is also effective to help the survival of green production industry.

Administrative policies could also help make the green and ordinary products less substitutable, such as the tax adjustments and subsidy for green products [72]. For example, a policy that requires all new government buildings to be green buildings, for example, would strongly restrict the substitution of green and ordinary products in the construction domain.

3.3.2 Dynamic Equilibrium

The market in the real world is dynamic as companies enter and leave the market. Therefore, in this section, we consider the dynamic equilibrium as companies enter and leave the competitive market.

The profits of an ordinary company $(\pi^O)^*$ and a green company $(\pi^G)^*$ under Nash equilibrium can be calculated as follows:

$$(\pi^O)^* = \frac{\left[(m+1)(a-\lambda^O - c^O) - m\theta(a-\lambda^G - c^G)\right]^2}{b\left[(n+1)(m+1) - nm\theta^2\right]^2}, \tag{3-13}$$

$$(\pi^G)^* = \frac{\left[(n+1)(a-\lambda^G - c^G) - n\theta(a-\lambda^O - c^O)\right]^2}{b\left[(n+1)(m+1) - nm\theta^2\right]^2}, \tag{3-14}$$

and the profit ratio is denoted by

$$\eta := \frac{(\pi^O)^*}{(\pi^G)^*} = \frac{\left[(m+1)(a-\lambda^O - c^O) - m\theta(a-\lambda^G - c^G)\right]^2}{\left[(n+1)(a-\lambda^G - c^G) - n\theta(a-\lambda^O - c^O)\right]^2}. \tag{3-15}$$

It is assumed that the number of ordinary companies is fixed since the ordinary production sector is relatively mature, however, there may be green companies entering or leaving the market. We also made the assumption that there is no entry or exit barrier (free entry/exit assumption). This is the drawback of this model since there is setup cost for most companies when they enter the market. This can be served as a future research direction which will be explained in detail later in this dissertation.

Suppose that the profit ratio η is the only incentive for entries and exits. If $\eta < 1$, more green companies will enter the market; and if $\eta > 1$, more green companies will exit the market. At the point when $\eta = 1$, the number of green companies under dynamic equilibrium is obtained:

$$m^* = \frac{(n+1)(a-\lambda^G - c^G) - (n\theta + 1)(a-\lambda^O - c^O)}{(a-\lambda^O - c^O) - \theta(a-\lambda^G - c^G)}. \tag{3-16}$$

If we set *m** to be greater than or equal to 1, then it yields the upper bound of substitution parameter θ (at least one green company to survive in the market under dynamic equilibrium):

$$\theta \le \frac{(n+1)(a-\lambda^G - c^G) - 2(a-\lambda^O - c^O)}{n(a-\lambda^O - c^O) - (a-\lambda^G - c^G)}. \quad (3\text{-}17)$$

This result also validate that smaller θ can better help green companies to survive in the fierce market competition.

3.3.3 Sensitivity Analysis

In this section, we analyze how sensitive the dynamic equilibrium is to the parameters: substitution factor parameter θ, green production cost c_G, long-term consumption price for green product λ_G and number of ordinary companies in the market n. The reason to conduct the analysis is that the parameters in the model may change or not be estimated accurately.

The market share of green products is utilized to characterize the equilibrium, since it is one of the most important indices to measure how green companies perform in the market. We define market share of green products as:

$$\beta := \frac{(\pi^G)^*}{(\pi^G)^* + (\pi^O)^*} = \frac{m[(n+1)(a-\lambda^G - c^G) - n\theta(a-\lambda^O - c^O)]}{m(n+1-n\theta)(a-\lambda^G - c^G) + n(m+1-m\theta)(a-\lambda^O - c^O)}. \quad (3\text{-}18)$$

Substituting *m** calculated in the previous section into the formula above gives us the market share of green products under dynamic equilibrium:

$$\beta = \frac{(n\theta+1)(a-\lambda^O - c^O) - (n+1)(a-\lambda^G - c^G)}{(n\theta - n+1)(a-\lambda^O - c^O) + (n\theta - n-1)(a-\lambda^G - c^G)}. \quad (3\text{-}19)$$

The methodology used to analyze the sensitivity of the equilibrium to the parameter is to take the partial derivatives of the market share with respect to the corresponding parameter.

1. Sensitivity of β to θ:

$$\frac{\partial\beta}{\partial\theta}=\frac{\partial}{\partial\theta}\left\{\frac{(n\theta+1)(a-\lambda^O-c^O)-(n+1)(a-\lambda^G-c^G)}{(n\theta-n+1)(a-\lambda^O-c^O)+(n\theta-n-1)(a-\lambda^G-c^G)}\right\}$$
$$=\frac{-n(\lambda^G+c^G-\lambda^O-c^O)\left[n(a-\lambda^O-c^O)+(n+1)(a-\lambda^G-c^G)\right]}{\left[(n\theta-n+1)(a-\lambda^O-c^O)+(n\theta-n-1)(a-\lambda^G-c^G)\right]^2}. \quad (3\text{-}20)$$
$$<0 \quad (\text{if } \lambda^G+c^G>\lambda^O+c^O)$$

Engineering and Managerial Insights:

As is discussed earlier, it is the green companies' interest to distinguish their products from the ordinary ones so that they are less substitutable, and θ is small. This result reinforces the importance of a smaller θ, which will increase the market share of green products under dynamic equilibrium, as long as the sum of cost and long-term price of the green product exceeds that of the ordinary one.

2. Sensitivity of β to c_G:

$$\frac{\partial\beta}{\partial c^G}=\frac{\partial}{\partial c^G}\left\{\frac{(n\theta+1)(a-\lambda^O-c^O)-(n+1)(a-\lambda^G-c^G)}{(n\theta-n+1)(a-\lambda^O-c^O)+(n\theta-n-1)(a-\lambda^G-c^G)}\right\}$$
$$=\frac{n(\theta-1)(a-\lambda^O-c^O)(n\theta+n+1)}{\left[(n\theta-n+1)(a-\lambda^O-c^O)+(n\theta-n-1)(a-\lambda^G-c^G)\right]^2}, \quad (3\text{-}21)$$
$$<0$$

Engineering and Managerial Insights:

- This result indicates that decreasing the manufacturing/production cost of green products will increase the market share under dynamic equilibrium.

- Although the improvements of technology are unlikely to be achieved in the near future to bring down the cost of green products to the ordinary level, a tax reduction is among the possible actions that could be taken by the government to reduce c^G.

3. **Sensitivity of β to λ_G:**

$$\begin{aligned}\frac{\partial\beta}{\partial\lambda^G} &= \frac{\partial}{\partial\lambda^G}\left\{\frac{(n\theta+1)(a-\lambda^O-c^O)-(n+1)(a-\lambda^G-c^G)}{(n\theta-n+1)(a-\lambda^O-c^O)+(n\theta-n-1)(a-\lambda^G-c^G)}\right\} \\ &= \frac{n(\theta-1)(a-\lambda^O-c^O)(n\theta+n+1)}{\left[(n\theta-n+1)(a-\lambda^O-c^O)+(n\theta-n-1)(a-\lambda^G-c^G)\right]^2} \\ &< 0 \end{aligned} \qquad (3\text{-}22)$$

As we can see, mathematically, $\frac{\partial\beta}{\partial\lambda^G} = \frac{\partial\beta}{\partial c^G} < 0$.

Engineering and Managerial Insights:

- As in the analysis for manufacturing/production cost c_G, decreasing the long-term consumption price of green products will increase the market share under dynamic equilibrium.
- Technology improvement is one of the possible actions to decrease λ_G, however, it is not likely to make a big impact in the short run.
- There are also other things that can be done to reduce λ_G, at least the general public's impression of it. As explained earlier, we assume that the customers' purchasing choices of green or ordinary products are not only based on the cash price ρ but also on the long-term price λ. The long-term price of green products λ^G (e.g., energy efficient light bulbs, solar powered products) is in many cases lower than that of the ordinary

products. However, this advantage may not be well realized by some customers, and thus the value of λ^G may be incorrectly perceived larger than it really is.

- We therefore suggest that, by increasing the public awareness of the long-term (both economical and environmental) advantage of green products, the market share of green products will increase under dynamic equilibrium. This is because it will make people's impression of λ_G much smaller, which is good for the survival of green production industry.

4. Sensitivity of β to n:

$$\begin{aligned}\frac{\partial\beta}{\partial n} &= \frac{\partial}{\partial n}\left\{\frac{(n\theta+1)(a-\lambda^O-c^O)-(n+1)(a-\lambda^G-c^G)}{(n\theta-n+1)(a-\lambda^G-c^G)+(n\theta-n-1)(a-\lambda^G-c^G)}\right\} \\ &= \frac{(\lambda_G+c_G-\lambda^G-c^G)\left[(a-\lambda^G-c^G)-\theta(a-\lambda^G-c^G)\right]}{\left[(n\theta-n+1)(a-\lambda^G-c^G)+(n\theta-n-1)(a-\lambda^G-c^G)\right]^2} \quad . \qquad (3\text{-}23) \\ &> 0 \quad (\text{if } \lambda^G+c^G>\lambda^O+c^O)\end{aligned}$$

Engineering and Managerial Insights:

- Perhaps counter-intuitively, this result means that, having more ordinary companies in the market will increase the market share of green products under dynamic equilibrium, as long as the sum of the cost and long-term price of the green product exceeds that of the ordinary one.

- Without detailed proof, we simply explain that, more ordinary companies will mitigate the market power and lower the average profit of an ordinary company, which consequently induces entries of more green companies taking up more market share.

In order to further demonstrate and explain the results and conclusions in this section, numerical examples using model formulation (A) are presented in the following section.

3.4 NUMERICAL EXAMPLE FOR MODEL (A)

In this section, numerical examples are presented for model formulation (A) which is introduced in the previous section. We use an example from the automobile industry to illustrate and further analyze the model.

We consider a market where there are $n(=100)$ automobile companies which produce ordinary cars (cars with conventional internal combustion engines) and m green companies which produces cars with little negative effect to the environment. The PHEV (Plug-in Hybrid Electric Vehicle) is chosen as the green product while the counter part of ordinary product is the Toyota Corolla 2008.

Model parameters:

- Production cost of ordinary product: production cost is assumed to be 70% of its manufacturer's suggested retail price. The suggest retail price for Toyota Corolla is $17,570 [73], therefore, the ordinary production cost is $c^O = \$12,299$.
- Long-term consumption cost of ordinary product: both gasoline costs and emission cost are calculated into the total long-term consumption cost term. Gasoline costs are based on a price of $3/gallon. The local and highway combined fuel economy for Toyota Corolla 2008 is 29 mpg [74]. The lifetime driving is assumed to be 150,000 miles. The emission costs are calculated to be

\$886 based on the study conducted by Lave and Maclean [75]. Therefore, the long-term consumption cost $\lambda^O = \$16{,}403$.

- Production cost of green product: PHEV is not commercially available yet and the production cost is estimated. The production cost of PHEV is believed to be 20% more expensive than that of a hybrid electric vehicle [76]. The suggested retail price for hybrid vehicle Toyota Prius is \$21,760 [77], therefore, the green production cost of PHEV is $c^G = \$26{,}112$.
- Long-term consumption cost of green product: same as the calculation for ordinary product, both gasoline costs and emission cost are calculated into the total long-term consumption cost term. The gasoline costs are based on a price of \$3/gallon. The combined fuel economy for PHEV is assumed to be 100 mpg [78]. The lifetime of the car is assumed to be 150,000 miles. The emission costs are calculated to be \$311 based on the study conducted by Lave and Maclean [79]. Therefore, the long-term consumption cost $\lambda^G = \$4811$.
- Demand function parameters are $a = 10(c^O + \lambda^O)$ and $b = 0.0001a$. Substitution parameter is set to be $\theta = 0.9$. This is due to the fact that PHEV and ordinary cars are very similar in terms of functionality.

We study this numerical example by answering the following questions.

1. How many green companies will be in the market under dynamic equilibrium, and how do they perform?

According to (3-16), the number of green companies in the market under dynamic equilibrium is 84.75. It means that before the 85th green company enters the market, green companies enjoy a higher average profit than that of the ordinary ones; while after 85 companies enter the market, their average profit falls to less than that of the ordinary ones.

Let us consider the situation when there are 85 green companies in the market. The performances of ordinary and green companies are compared in Table 4:

Table 4 A comparison of ordinary and green companies under dynamic equilibrium

	Ordinary (Toyota Corolla)	Green (PHEV)
Number of companies	100	84.75 →85
Production of a single company	50.63→51	50.76→51
Market supply	5063	4315
Cost ($)	12299	26112
Cash price ($)	13756	27565
Long-term price ($)	16403	4811
Profit of a single company ($)	73954	73574
Market share	54%	46%

We see from Table 4 that the overall market share of green products is relatively low at market equilibrium. However, the real scenario is even worse. Nowadays, there is no Plug-in Hybrid Electric Vehicle which is commercial available in the market. Therefore, compared to the market equilibrium from the analysis above, green production industry has a lot room to grow, which is good news for green companies. On the other hand, this also tells us that there must be some reasons why green products are not popular and widely accepted yet as they should be.

In the following section, analyses are conducted to investigate how the change of parameters will affect the market share of green products and how we can help green production industry to better survive and thrive.

2. How does the production cost for green product c^G affect the dynamic equilibrium?

In this scenario, the cost of green products is reduced by 10% due to tax reduction, and the dynamic equilibrium is summarized in Table 5.

Table 5 A summary of dynamic equilibrium after 10% reduction of green production cost

	Ordinary (Toyota Corolla)	Green (PHEV)
Number of companies	100	102.9 → 103
Production of a single company	46.48→46	46.45→46
Market supply	4648	4784
Cost ($)	12299	23501
Cash price ($)	13633	24834
Long-term price ($)	16403	4811
Profit of a single company ($)	62003	61921
Market share	49.3%	50.7%

As we can see from the table, decreasing the green production cost has increased its market share from 46% to 51%.

This scenario also demonstrates the effectiveness of tax reduction/subsidies for the growth of green companies from a theoretical point of view, since tax reduction/subsidies are somewhat equivalent to reducing green production cost.

- In the short run, tax benefits for PHEV consumers and/or subsidy to PHEV manufacturers can help the survival of PHEV in the market
- In the long run, PHEV manufacturers should work on improving the technology to bring down its production cost, which can help PHEV to survive and thrive in the automobile market.

3. How does long-term green consumption price λ^G affect the dynamic equilibrium?

In this scenario, we consider how the long-term consumption price affects the market competition and the dynamic equilibrium.

Nowadays, the long-term price advantage of green products over ordinary ones is under realized. For example, the consumers probably know that the compact fluorescent light bulbs are more expensive and will save electricity. However, they may not be aware that a compact fluorescent saves $62 over its lifetime [80], comparing with a ordinary light bulb.

Therefore, here we assume that the long-term consumption price for green product (PHEV) λ^G is incorrectly perceived to be 10% larger than its true value. $(\lambda^G)' = 110\% \cdot \lambda^G = 5292$.

Table 6 A summary of dynamic equilibrium after 10% increase of long-term price for PHEV

	Ordinary (Toyota Corolla)	Green (PHEV)
Number of companies	100	81.74 → 82
Production of a single company	51.55→52	51.40→51
Market supply	5155	4215
Cost ($)	12299	26112
Cash price ($)	13779	27587
Long-term price ($)	16403	5292
Profit of a single company ($)	76271	75837
Market share	55%	45%

As we can see from Table 6, an increase of PHEV's long-term consumption price will decrease the market share of PHEV.

As discussed in section 3.3.3, long-term consumption price can transform to gas consumption over PHEV's lifetime, the consumers' awareness of this advantage and the environment effects.

One approach to increase PHEV's market share is to further improve its technology so that it can save more money for consumers. Another approach which is easier to achieve in the short run is to increase the public awareness of the green products' economical and environmental advantage. This can be done through educational program or marketing campaign.

4. How does θ affect the dynamic equilibrium?

In this scenario, the green (PHEV) companies further distinguish their products from its counterpart Toyota Corolla with $\theta = 0.8$. This could be accomplished by improving the internal design of the products, or by better appearance design, or by administrative requirement, or by increased public awareness/preference of green products.

The resulting dynamic equilibrium is summarized in Table 7:

Table 7 A summary of dynamic equilibrium after substitution parameter θ reduced to 0.8

	Ordinary (Toyota Corolla)	Green (PHEV)
Number of companies	100	92.4→ 92
Production of a single company	51.44→51	51.69→52
Market supply	5144	4756
Cost ($)	12299	26112
Cash price ($)	13775	27576
Long-term price ($)	16403	4811
Profit of a single company ($)	75946	76697
Market share	52%	48%

As we can see from the computational results, decreasing the substitution parameter θ can help green products (PHEV) survive in the market competition. Therefore, these results further demonstrate the importance of reducing the substitution parameter.

PHEV manufacturer could consider launching marketing campaign and/or design unique appearance in the short run. In the long run, improving the internal design and technology can be done to gain the competitive edge in the market.

3.5 MODEL (B) FORMULATION

In real life, the process of green products penetrating into the manufacturing/production sector and then into the competitive market often begins with introducing green production departments in the ordinary production companies. For example, Toyota produces both conventional internal combustion engine cars, such as Corolla, Avalon, Camry and hybrid electric vehicle, such as Prius and Touring [81].

Companies introduce green manufacturing sector either due to legislation or marketing considerations at the green production initiation stage. Many green companies would have a mixture of both green and ordinary production sectors in the same company.

In this section, we consider the scenario where green and ordinary productions are not carried out in separate companies. Model formulation (B) is the extension of model formulation (A) by considering the scenario where there are both green and ordinary production sectors in the same company.

3.5.1 The Cournot Model and the Nash Equilibrium

In the model formulation (B), companies are not divided into two distinct categories (ordinary and green company); instead, each company can produce both ordinary and green products. We call them "hybrid" companies. Their decision problem is to determine how many of each type of products (green or ordinary) to produce in order to maximize their own profits.

Model formulation:

Suppose there are *s* such "hybrid" companies in the market. The majority of mathematical notations are same as in model formulation (A).

Given the total quantities of ordinary and green products by other companies $Q_{-k}^O = \sum_{i=1}^{s} q_i^O - q_k^O$ and $Q_{-k}^G = \sum_{i=1}^{s} q_i^G - q_k^G$, the profit of company *k* is:

$$\begin{aligned}
&\pi_k(q_k^O, q_k^G; Q_{-k}^O, Q_{-k}^G) \\
&= (\rho^O - c^O)q_k^O + (\rho^G - c^G)q_k^G \\
&= (p^O - \lambda^O - c^O)q_k^O + (p^G - \lambda^G - c^G)q_k^G \\
&= \left[a - b\left(q_k^O + Q_{-k}^O + \theta Q^G\right) - \lambda^O - c^O\right]q_k^O + \left[a - b\left(q_k^G + Q_{-k}^G + \theta Q^O\right) - \lambda^G - c^G\right]q_k^G \\
&= -b\left(q_k^O\right)^2 - b\left(q_k^G\right)^2 - 2b\theta q_k^O q_k^G + \left[a - b\left(Q_{-k}^O + \theta Q^G\right) - \lambda^O - c^O\right]q_k^O + \left[a - b\left(Q_{-k}^G + \theta Q^O\right) - \lambda^G - c^G\right]q_k^G
\end{aligned}$$

(3-24)

To obtain the best response of company *k*, we set the first derivative of $\pi_k(q_k^O, q_k^G; Q_{-k}^O, Q_{-k}^G)$ to be zero:

$$\begin{bmatrix} \dfrac{\partial \pi_k}{\partial q_k^O} \\[2ex] \dfrac{\partial \pi_k}{\partial q_k^G} \end{bmatrix} = \begin{bmatrix} a - \lambda^O - c^O - b(Q_{-k}^O + \theta Q_{-k}^G) \\ a - \lambda^G - c^G - b(Q_{-k}^G + \theta Q_{-k}^O) \end{bmatrix} - \begin{bmatrix} 2b & 2b\theta \\ 2b\theta & 2b \end{bmatrix} \begin{bmatrix} q_k^O \\ q_k^G \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

(3-25)

Therefore, the best response of company *k* is:

$$\begin{bmatrix}(q_k^O)^*\\(q_k^G)^*\end{bmatrix}=\begin{bmatrix}2b & 2b\theta\\2b\theta & 2b\end{bmatrix}^{-1}\begin{bmatrix}a-\lambda^O-c^O-b(Q_{-k}^O+\theta Q_{-k}^G)\\a-\lambda^G-c^G-b(Q_{-k}^G+\theta Q_{-k}^O)\end{bmatrix}$$
$$=\frac{1}{4b(1-\theta^2)}\begin{bmatrix}2 & -2\theta\\-2\theta & 2\end{bmatrix}\begin{bmatrix}a-\lambda^O-c^O-b(Q_{-k}^O+\theta Q_{-k}^G)\\a-\lambda^G-c^G-b(Q_{-k}^G+\theta Q_{-k}^O)\end{bmatrix}$$

(3-26)

To prove that this is the maximum rather than a saddle point, we can take the second derivatives:

$$\frac{\partial^2\pi_k}{\partial^2(q_k^O)^2}=-2b<0 \tag{3-27}$$

$$\frac{\partial^2\pi_k}{\partial^2(q_k^G)^2}=-2b<0 \tag{3-28}$$

$$\frac{\partial^2\pi_k}{\partial(q_k^G)\partial(q_k^O)}=-2b\theta \tag{3-29}$$

$$\frac{\partial^2\pi_k}{\partial(q_k^O)^2}\frac{\partial^2\pi_k}{\partial(q_k^G)^2}-\left[\frac{\partial^2\pi_k}{\partial(q_k^G)\partial(q_k^O)}\right]^2=-4b^2(1-\theta^2)<0 \tag{3-30}$$

Under Cournot-Nash equilibrium, we have $(Q_{-k}^O)^*=(s-1)(q_k^O)^*$ and $(Q_{-k}^G)^*=(s-1)(q_k^G)^*$. Substituting these two equations into equation for the best response of company *k* above, we have the quantity supply under equilibrium:

$$\begin{bmatrix}(q_k^O)^*\\(q_k^G)^*\end{bmatrix}=\frac{1}{b(s+1)}\begin{bmatrix}1 & \theta\\\theta & 1\end{bmatrix}^{-1}\begin{bmatrix}a-\lambda^O-c^O\\a-\lambda^G-c^G\end{bmatrix}$$
$$=\frac{1}{b(s+1)(1-\theta^2)}\begin{bmatrix}1 & -\theta\\-\theta & 1\end{bmatrix}\begin{bmatrix}a-\lambda^O-c^O\\a-\lambda^G-c^G\end{bmatrix} \tag{3-31}$$
$$\forall k=1,\cdots,s.$$

3.5.2 Sensitivity Analysis

In this section, we analyze how sensitive the equilibrium is to the parameters: substitution factor parameter θ, green production cost c_G, long-term consumption price for green product λ_G and number of hybrid companies in the market n.

The market share of green products under Cournot-Nash equilibrium is the same as in model formulation (A):

$$\begin{aligned}\beta^G &= \frac{(Q^G)^*}{(Q^G)^* + (Q^O)^*} \\ &= \frac{(q^G)^*}{(q^G)^* + (q^O)^*} \\ &= \frac{a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)}{(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)}\end{aligned} \tag{3-32}$$

The methodology used to analyze the sensitivity of the equilibrium to the parameter is also by taking the partial derivatives of the market share with respect to the corresponding parameters.

1. **Sensitivity of β^G to θ:**

$$\begin{aligned}\frac{\partial \beta^G}{\partial \theta} &= \frac{\partial}{\partial \theta}\left[\frac{a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)}{(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)}\right] \\ &= \frac{-(a - \lambda^O - c^O)(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)}{[(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)]^2} \\ &\quad + \frac{(2a - \lambda^O - c^O - \lambda^G - c^G)[a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)]}{[(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)]^2} \\ &= \frac{-(a - \lambda^O - c^O)(1-\theta) + a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)}{[(1-\theta)]^2(2a - \lambda^O - c^O - \lambda^G - c^G)} \\ &= \frac{\lambda^O + c^O - \lambda^G - c^G}{[(1-\theta)]^2(2a - \lambda^O - c^O - \lambda^G - c^G)}\end{aligned} \tag{3-33}$$

If $\lambda^O + c^O < \lambda^G + c^G$, then $\frac{\partial \beta^G}{\partial \theta} < 0$. This is true in most cases nowadays since cost of green production is often significantly higher than ordinary ones.

Engineering and Managerial Insights:

As long as the sum of cost and long-term price of the green product exceeds that of the ordinary one, a smaller substitution parameter is beneficial to increase the green market share.

Distinguishing green products from ordinary ones will help the growth of green production sector. Toyota Prius is popular not only because of the hybrid feature, but also due to its unique appearance. This conclusion is similar to the result derived from the model formulation (A).

2. Sensitivity of β^G to c^G:

$$\frac{\partial \beta^G}{\partial c^G} = \frac{\partial}{\partial c^G}\left[\frac{a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)}{(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)}\right]$$

$$= \frac{-(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)}{[(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)]^2} + \frac{[a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)](1-\theta)}{[(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)]^2}$$

$$= \frac{-(2a - \lambda^O - c^O - \lambda^G - c^G) + [a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)]}{(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)^2}$$

$$= \frac{-(1+\theta)(a - \lambda^O - c^O)}{(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)^2} \tag{3-34}$$

Engineering and Managerial Insights:

This result is similar as in model formulation (A). Decreasing the green production cost can help the growth of green production industry.

- In the short run, this can be achieved by subsidy to green product manufacturers and tax credit or tax deduction to green product consumers. According to Richard A. Chapo [82], for Toyota Prius, the tax credits that come with each purchase certainly add to their popularity.
- In the long run, green companies should take steps to improve the production technology to bring down the cost. Watanabe, one of Toyota's top executives, said, "we need to improve the production engineering and develop better technology in batteries, motors, and inverters, and my quest is to produce a third-generation Prius quickly and cheaply." [83]

3. Sensitivity of β^G to λ^G:

$$
\begin{aligned}
\frac{\partial \beta^G}{\partial \lambda^G} &= \frac{\partial}{\partial \lambda^G}\left[\frac{a-\lambda^G-c^G-\theta(a-\lambda^O-c^O)}{(1-\theta)(2a-\lambda^O-c^O-\lambda^G-c^G)}\right] \\
&= \frac{-(1-\theta)(2a-\lambda^O-c^O-\lambda^G-c^G)}{[(1-\theta)(2a-\lambda^O-c^O-\lambda^G-c^G)]^2} + \frac{(1-\theta)[a-\lambda^G-c^G-\theta(a-\lambda^O-c^O)]}{[(1-\theta)(2a-\lambda^O-c^O-\lambda^G-c^G)]^2} \\
&= \frac{-(2a-\lambda^O-c^O-\lambda^G-c^G)+[a-\lambda^G-c^G-\theta(a-\lambda^O-c^O)]}{(1-\theta)(2a-\lambda^O-c^O-\lambda^G-c^G)^2} \\
&= \frac{-(1+\theta)(a-\lambda^O-c^O)}{(1-\theta)(2a-\lambda^O-c^O-\lambda^G-c^G)^2} < 0
\end{aligned}
$$

(3-35)

Engineering and Managerial Insights:

- Decreasing the long-term consumption price of green products will increase the market share under dynamic equilibrium.
- Public awareness effects are incorporated into the long-term consumption price. For example, the long-term consumption price for Toyota Prius includes the customer's impression of the gasoline cost over its driving lifetime as well as the negative effect (cost) to the environment.
- Educational programs to increase the public awareness will be very useful. This is because that decreasing the consumer's conception of long-term consumption price of green products is good for the green production.

4. Sensitivity of β^G to *n*:

$$\beta^G = \frac{(Q^G)^*}{(Q^G)^* + (Q^O)^*} = \frac{(q^G)^*}{(q^G)^* + (q^O)^*}$$

$$= \frac{a - \lambda^G - c^G - \theta(a - \lambda^O - c^O)}{(1-\theta)(2a - \lambda^O - c^O - \lambda^G - c^G)}$$

As we can see, $\frac{\partial \beta^G}{\partial n} = 0$, therefore, a change in the number of companies in the market won't change the market equilibrium.

Engineering and Managerial Insights:

- The number of companies in the market will not affect the market share of green production industry. Therefore, a company entering and leaving the market won't affect the market equilibrium. Note that this conclusion is different from result derived from model formulation (A).

- One explanation is that every company will produce same mixture of green and ordinary products at market equilibrium. They are assumed to be symmetric at market equilibrium. Therefore, what really affects the market share of green products is the percentage of green and ordinary production of each company at the equilibrium.

3.6 NUMERICAL EXAMPLE FOR MODEL (B)

In this section, we demonstrate and validate model formulation (B) with some numerical examples. Part of the data utilized here is the same as in the numerical examples section of model formulation (A) for the purpose of illustration and comparison.

We consider a market where there are $n(=100)$ automobile companies which produce both ordinary cars (cars with conventional internal combustion engine) and green cars with little negative effect to the environment. Toyota Prius (a hybrid electric vehicle in the automobile market) is chosen as the green product while its counterpart as the ordinary product is the Toyota Corolla 2008.

Model parameters:

- Production cost and long-term consumption cost of ordinary product: we use the same product (Toyota Corolla 2008) as ordinary product in both models, therefore, these two parameters stay the same: $c^O = \$12{,}299$ and $\lambda^O = \$16{,}403$.

- Production cost of green product: hybrid electric vehicle is said to be far more expensive than the manufacturer's suggested price [84]. Due to the fact that the hybrid electric vehicle production technology and sales has been improved a lot [85], we assume that the production cost of Toyota Prius is same as its listed price which is $21,760 [86].
- Long-term consumption cost of green product: both gasoline costs and emission costs are calculated into the total long-term consumption cost term. The gasoline costs are based on a price of $3/gallon. The local and highway combined fuel economy for Toyota Prius is 46 mpg [87]. The lifetime driving is assumed to be 150,000 miles. The emission costs are calculated to be $440 based on the study conducted by Lave and Maclean [88]. Therefore, the long-term consumption cost $\lambda^G = \$10{,}223$.
- Demand function parameters are $a = 10(c^O + \lambda^O)$ and $b = 0.0001a$. Substitution parameter is set to be $\theta = 0.9$. This is due to the fact that HEV and ordinary cars are very similar in terms of functionality.

We study this numerical example by answering the following questions:

1. How do hybrid companies perform in the market competition?

The market equilibrium scenario which compares the green car (Toyota Prius) production and ordinary car (Toyota Corolla) production sectors is summarized in table 8.

Table 8 A comparison of ordinary and green car production sectors under market equilibrium

	Ordinary Sector (Toyota Corolla)	Green Sector (Toyota Prius)
Production of a single company	52.26→52	40.94→41
Market supply	5226	4094
Cost ($)	12299	21760
Cash price ($)	14857	24285
Long-term price ($)	16403	10223
Profit of a single company ($)	133660	103380
Market share	56.07%	43.93%

We see from Table 8 that the overall market share of green products is relatively low. However, comparing the current automobile market situation and the market equilibrium derived here, there is still room for growth in the green production industry. Therefore, the objective here is to find out how green production industry can better survive and occupy more market share. This is done by investigating some other scenarios when model parameters change.

2. How does production cost of the green product (Toyota Prius) c^G affect the dynamic equilibrium?

In this scenario, the cost of green products is reduced by 10% due to tax reduction, and the market equilibrium is summarized in Table 9:

Table 9 A summary of market equilibrium after 10% reduction of green production cost

	Ordinary Sector (Toyota Corolla)	Green Sector (Toyota Prius)
Production of a single company	48.71→49	44.89→45
Market supply	4871	4489
Cost ($)	12299	19584
Cash price ($)	14857	22131
Long-term price ($)	16403	10223
Profit of a single company ($)	124570	114330
Market share	52.04%	47.96%

As we can see from Table 9, under market equilibrium, the market share of Toyota Prius has increased by 4% when the production cost of Toyota Prius has decreased by 10%. This might not be feasible in the short run, however, tax credit or subsidy for consumers and manufacturers respectively can achieve this goal in the near future. This scenario demonstrates the effectiveness of subsidy/tax reduction for green companies.

3. How does long-term consumption price for a green product (Toyota Prius) λ^G affect the dynamic equilibrium?

In this scenario, we consider how the long-term consumption price affects the market competition and the dynamic equilibrium.

Nowadays, the long-term price advantage of green products over ordinary ones is under realized. For example, the consumers probably know that Toyota Prius is more expensive and will save gasoline consumption over the lifetime. However, they may not be aware Toyota Prius can save over $6,000 over its driving lifetime.

In this scenario, the long-term price advantage of green products (Toyota Prius) over ordinary counterparts (Toyota Corolla) is unrealized, and λ^G is incorrectly perceived to be 10% larger than its true value: $(\lambda^G)' = 110\% \cdot \lambda^G = \$11245$.

The dynamic equilibrium is summarized in Table 10:

Table 10 A summary of market equilibrium after 10% increase of long-term price for Prius

	Ordinary Sector (Toyota Corolla)	Green Sector (Toyota Prius)
Production of a single company	53.93→54	39.09→39
Market supply	5393	3909
Cost ($)	12299	21760
Cash price ($)	14857	24275
Long-term price ($)	16403	11245
Profit of a single company ($)	137930	98302
Market share	57.98%	42.02%

This scenario also demonstrates the importance of public awareness of the green products' economical and environmental advantage, since it is easier to achieve in the short run.

4. How does substitution parameter θ affect the market equilibrium?

Suppose the green companies further distinguish their products with $\theta = 0.8$. This could be accomplished by improving the design of the products, or by administrative requirement, or by increased public preference for green products. The resulting market equilibrium is summarized in Table 11:

Table 11 A summary of market equilibrium after substitution parameter θ reduced to 0.8

	Ordinary Sector (Toyota Corolla)	Green Sector (Toyota Prius)
Production of a single company	52.02→52	46.36→46
Market supply	5202	4636
Cost ($)	12299	21760
Cash price ($)	14857	24285
Long-term price ($)	16403	10223
Profit of a single company ($)	133050	117070
Market share	52.88%	47.12%

As we can see from the computational results, the decrease in the substitution parameter can lead to an increase in the market share for green product (Toyota Prius). These results further demonstrate the importance of reducing the substitution parameter.

3.7 CONCLUSIONS

In this part of my dissertation, game theoretic models are formulated to study the competition between ordinary and green companies/manufacturing sectors which produce the same type of products with different techniques and costs.

In model formulation (A), companies are divided into two types: green companies which produce green products and ordinary companies which produce ordinary products. The competition among them is assumed to be Cournot. Each company independently and simultaneously determines their supply quantities in order to maximize their own profits.

The Nash equilibrium as well as the dynamic equilibrium under the free entry/exit assumption is obtained. The main drawback of this model is the free-entry/exit assumption since for some manufacturer, the setup cost when they enter the market is significant. Therefore, this is the possible extension for this model. However, for the purpose of market analysis in this research problem, after the manufacturer enters the market, the setup cost won’t affect their decision choices anymore. Therefore, for mass production scenario, this mathematical decision making model can be applied with no restriction.

Sensitivity analysis is also used to study the possible actions that could be taken to help increase the market share of green products in the market. These results are demonstrated with numerical examples.

The engineering and managerial insights are summarized as follows.

Engineering and Managerial Insights:

1. Green companies need to distinguish their products from ordinary counterparts to survive in the market.

2. Public awareness of the advantage of green products is important for the healthy growth of green companies.

3. Subsidy/tax reduction could help increase the market share of green products in the market.

In model formulation (B), each company is assumed to produce both ordinary and green products. We call them “hybrid” companies. Same as in model formulation (A), each company independently and simultaneously determines their supply quantities in order to maximize their own profits. The competition among them is also assumed to be Cournot.

The Nash equilibrium for this game theory model is obtained. Sensitivity analysis is also used to study the possible actions that could be taken to help increase the market share of green products in the market. These results are demonstrated with numerical examples.

The engineering and managerial insights are summarized as follows.

Engineering and Managerial Insights:

1. Green manufacturing sectors need to distinguish their products from ordinary ones to gain competitive edges in the market.
2. Public awareness of the advantage of green products is important for the healthy growth of green manufacturing sectors in the companies.
3. Subsidy/tax reduction could help increase the market share of green products in the market.

In summary, no matter the manufacturer is a pure green production company or one production sector in a hybrid company, the conclusions are similar. To distinguish green products from their ordinary counterparts, to increase public awareness and to impose tax benefits are among the effective policies/methods to better help green production industry survive and thrive in the fierce market competition.

The major contribution of this game theory study is to provide a new perspective to analyze the market competition between green and ordinary production industries. The effects of the government and regulatory organizations interventions are considered, such as tax reduction/subsidy for green products, standard on carbon dioxide emission and education for public awareness. The dynamic equilibrium and sensitivity analysis address more realistic market scenarios. The mathematical model can provide both engineering and managerial insights for the manufacturers, consumers and the government regulatory department.

4.0 LONG TERM PROFIT-DRIVEN DECISION MAKING IN PRODUCT MARKET LIFECYCLE MANAGEMENT

New product decision making is critical to the sustainable development of a manufacturing company. A key element in corporate strategy is identifying the best investment decision at each phase of a product's lifecycle. This study considers a sequential decision making process through each stage of a product lifecycle. This problem is formulated as a Markov decision process (MDP) model where optimal sequential investment decisions are based on the product lifecycle phases, market competition and seasonal demand so as to maximize the long-term profit. The approach is demonstrated with realistic numerical examples, and guidelines are developed for strategic decision making for companies.

4.1 INTRODUCTION

The landscape of the world economy has changed significantly over the last twenty five years. The inter-connectedness of national economies and the rapid ascent of the BRIC countries (Brazil, Russia, India, China) in the global engineering environment have forced organizations to become more competitive with little room for error in product lifecycle decisions. A large percentage of organizational revenues are derived from products introduced in the recent years. At DuPont [89], sales from new products (products that launched in the last five years) accounted for 36 percent of the company's revenue in 2007. This number is up from 24 percent in 2001. Therefore, in order to maintain and increase market share, new products must be continuously introduced into the market as old ones are phased out. For example, Canon Company introduces new models of digital cameras every couple of months to maintain the competitive edge in the camera industry. Critical product resource allocation decisions are made at each stage in the product lifecycle in order to achieve sustainable development of the company.

Product lifecycle theory has been a key organizing principle in studies of technical innovation and has been recognized by leading management teams as a tool for strategic decision making [90]. In this study, we consider sequential decisions that must be made throughout the lifecycle of an organization's products, especially in lifecycle elements after the product enters a competitive market. Quantitative models are developed to assist decision making in the broad spectrum of supply chain management.

In general, supply chain management decision making is usually categorized into three levels: strategic, tactical and operational. Figure 10 provides a visual demonstration of the decision relationships within the three levels of the supply chain [91].

Strategic level decisions are usually long-term decisions that involve designing the entire supply chain. These decisions typically relate to issues like production size, location, storage size, and transportation network design decision.

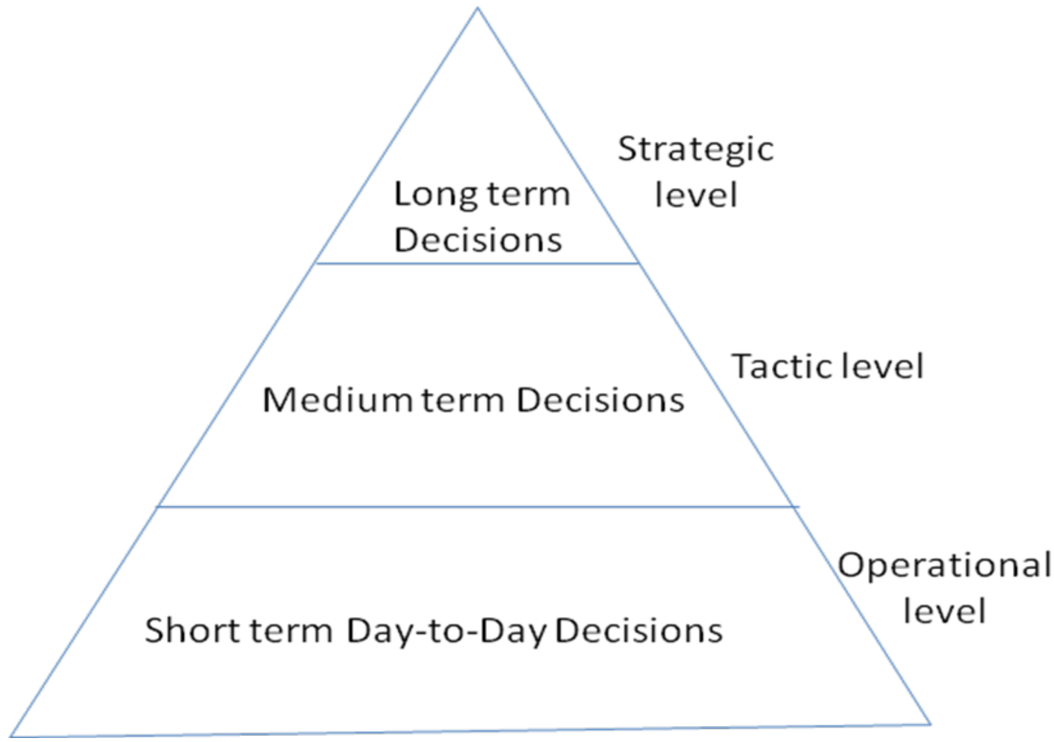

Figure 10 Categories of Supply chain decisions

Tactical decisions are medium term decisions which are made at monthly/quarterly basis. These include demand forecasting, distribution planning, production scheduling and material requirement planning, distribution and transportation planning, etc. Operational level decisions are often concerned with short-term decisions that are related to day-to-day operations. These include make-or-buy decisions, work shift scheduling, shipping arrangements, etc.

This part of the dissertation study considers product decision making at the tactical level. The product lifecycle model presented here is developed with the objective to maximize the long-term total discounted profit of the entire company. Companies make decisions that have both immediate and long-term consequences. Decisions must not be made in isolation; today's decisions impact tomorrow's choices. For example, if Canon decides to launch a new digital camera, it will affect a series of subsequent decisions, such as human resource allocation, facility layout, packing, marketing, etc.

The Markov decision process is an effective technique in modeling sequential decision making, especially under uncertainty [92]. At a specified point in time, a decision maker must choose an action. This choice produces an immediate reward or cost. As a result of the action/choice, the system evolves to a new state. At the next point in time, based on a probability distribution, the decision maker will again face a similar situation. The system might now be in a different state with a different set of available actions to choose. The goal of this decision making model is provide a mechanism to develop an optimal policy. With the optimal policy, decision makers can choose a sequence of actions at corresponding lifecycle stages that make the system perform optimally with respect to predetermined performance criteria (e.g. maximizing company profits).

The remainder of this chapter is organized as follows: a literature review of relevant studies is introduced in section 4.2; the lifecycle decision model formulation is introduced in section 4.3 and includes the scenario description in section 4.3.1, model assumptions in section 4.3.2 and model parameters in section 4.3.3. In section 4.4, we demonstrate our approach with several realistic numerical examples, analyze the computational results, compare alternative scenarios and then derive guidelines for corporate decision makers. The chapter concludes with a summary of the results and possible future research extensions in section 4.5.

4.2 LITERATURE REVIEW

The majority of existing literature on decision making in product lifecycle management focuses on the new product development phase before it enters the market. Further, the methodologies used in decision making analysis are mainly focused on a conceptual rather than a quantitative perspective.

Ali, Krapfel and Labahn [93] define product lifecycle time to be the elapsed time from the beginning of an idea to the end of the product launch and do not consider the decision making after the products are released into the competitive market. Both Olson et al. [94] and Srinivasan, Lovejoy and Beach [95] discuss methodologies that incorporate the product marketing information into new product development.

Schmidt, Montoya-Weiss and Massey [96] conduct an experiment to examine the effectiveness of new product development project continuation decisions. Their suggestion is that teams make more effective decisions than individuals, and virtual teams (not communicating face-to-face) make the most effective decisions. This study is qualitative orientated. Day [97] discusses the factors that determine the progress of the product through the stages of the lifecycle and the role of the product lifecycle concept in the formulation of competitive strategy.

In this study, we take a stochastic dynamic programming approach to develop a product lifecycle decision making model for sequential decision making in the process, especially for the lifecycle stages after it has been released to the market. This idea is similar as the concept in product lifecycle assessment/cradle-to-grave analysis. The purpose of LCA is often referred to as comparing the environmental effects all through products' lifecycle so able to choose the least burdensome one [98].

Papadakis, Lioukas and Chambers [99] investigate the relationship between the process of strategic decision making and the contextual factors. They analyze the decision making process by drawing on a sample of strategic decisions and studying the dimensions in the strategic decision making. Decision-specific characteristics, top management characteristics, and contextual factors (external corporate environment and internal firm characteristics) are considered. The conclusions are that strategic decision processes are shaped by various factors and that decision specific characteristics appear to have the most important influence on the strategic decision making process. In this study, we adopted the similar idea by considering the competition from both inside and outside the company.

The investment decision is one of the most important decisions in corporate decision making. Slovic, Fleissner and Bauman [100] studied to understand the process of investment decision making from the aspect of economics, finance and psychology. This research focuses on the use of information in investment decisions; the methodologies include simulation, linear modeling and statistical modeling. In this study, we choose corporate support/investment decision as a major decision to make in the process.

As for the methodology used for this study, the Markov decision process has been popular in machine maintenance, finance and biology problems. D. J. White [101] conducted a survey on application of Markov decision processes. Applications are categorized into 18 areas, some of which are population harvesting, epidemics, sales promotions. Altman [102] did a survey of applications of Markov decision processes in communication networks. Theoretical MDP tools as well as applications in communication networks are developed to solve network control problems. The approach was to control the transition probabilities in the MDP model. Markov decision process methodology has been used widely in control of network of queues as well. There has been some characterization of the structure of optimal policies in these network queue control problem [103].

As for the MDP decision making criteria, D. J. White [104] did a survey of nonstandard MDP criteria which means those which do not seek simply to optimize expected returns per unit time or expected discounted return. It covers infinite-horizon non-discounted formulations, infinite-horizon discounted formulations, and finite-horizon formulations.

The major contribution of this study is the consideration of the sequential decision making involved in product lifecycle management from a quantitative perspective. There has been little research work done in this perspective to the best of my knowledge. It is demonstrated that the Markov decision process is a suitable methodology for this problem since it takes into account both the outcome of current decisions and future decision making opportunities.

4.3 MODEL FORMULATION

The model formulation is introduced in the following section including the scenario description, MDP methodology introduction, model assumptions and model parameters.

4.3.1 Scenario Description

Consider the following scenario: A company manufactures and manages *M* products. Each of the products may be in different phases of their lifecycles. Products evolve through the lifecycle based on manufacturing, marketing, and competitive constraints. After a product has reached its end-of-life phase, the company may invest in another new product, but the number of active products in market is limited due to budgetary constraints. The selling price and profitability of these products are assumed to be known from R&D departments, and market demand follows seasonal fluctuations. Each of the products in the market competes with a similar/same style of products (sold by competing companies) in the market and occupies a proportion of the total market demand.

Ideally, a company would like to keep all of its products in the mature phase as long as possible, since the maturity phase is assumed to be the most profitable lifecycle phase. On the other hand, when a product gradually and inevitably loses market share, the company may want to let it phase out and introduce new products into the market. At each step of the product lifecycle, the decision maker is faced with the decision of whether or not to invest in an existing product by upgrading it, repackaging it, initiating a new marketing campaign, and so on. This process is analogous to the stage gate process that has been validated at many diverse organizations over the last decade [105]. The company's objective is to maximize its long-term total expected discounted profit, and the core issue here is to make effective and optimal sequential investment decisions based on demand fluctuations and market competition to achieve the objective.

4.3.2 Introduction to MDP Methodology

Markov Decision Processes, which is also referred to as stochastic dynamic programming or stochastic control process, deals with decision making problems where the outcomes are uncertain [106]. It was developed around the 1950s and Bellman was the first to use the name "Markov decision process". Since then, the Markov decision process has been a popular methodology in the application area of engineering, biology, finance etc. Some of the traditional applications include inventory control problems, maintenance and replacement problem and behavioral ecology problems.

Markov decision process methodology is a special case of sequential decision making model. Figure 11 below gives a symbolic representation of a sequential decision problem [54]:

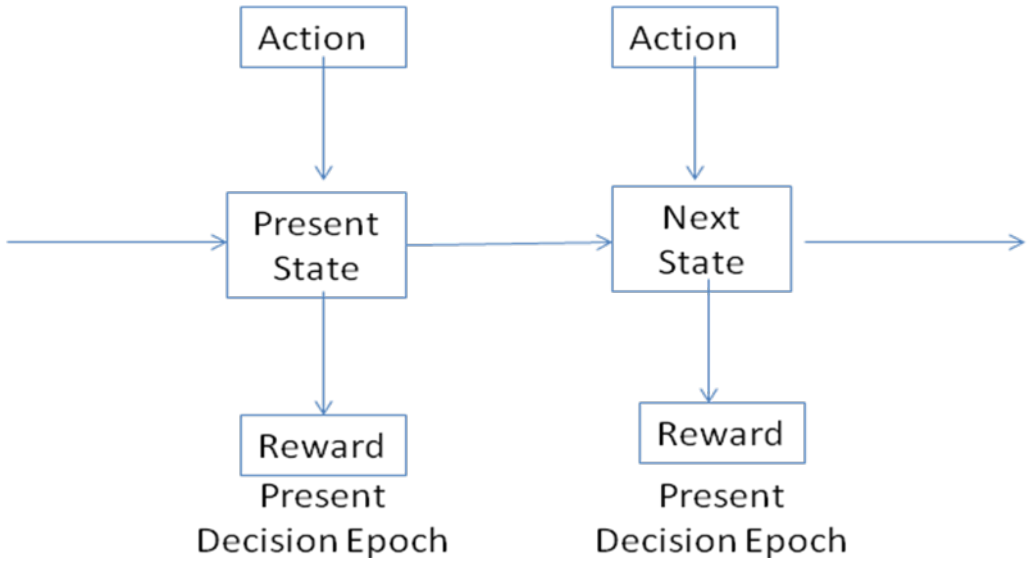

Figure 11 Symbolic representation of a sequential decision problem

In a Markov decision making problem, at each decision epoch, decision maker chooses an action at a certain state will generate a reward/cost and determine the next state at the following period.

Now, we introduce basic modeling elements for a Markov decision process model.

MDP Model Elements:

1. A set of decision epochs;
2. A set of system states;
3. A set of available actions;
4. A set of state and action dependent immediate rewards or costs;

5. A set of state and action dependent transition probabilities.

MDP Model Solution Techniques:

There are mainly three types of solution techniques to solve a Markov decision process model. However, it should be noted that, each type of solution technique has variants depending on the property of the MDP problem.

1. Value iteration:

Value iteration is one of the most widely used algorithms for solving Markov decision process problem.

The basic idea is that by applying the optimality operator again and again, we will get a sequence of values which is getting closer and closer to the true optimal value. When the two successive values are very close to each other, algorithm will stop and optimal decision rules can be calculated from the optimality equation. The mathematical theorem behind value iteration algorithm is the fixed point theorem.

2. Policy iteration:

Instead of applying the optimality operator again and again to get a sequence of values which is getting closer to the true optimal value, policy iteration follows a different sequence of achieving the optimality.

Policy iteration follows the sequence of first policy evaluation with the previous decision rule and then policy improvement with the previous policy value. In other words, it has an alternating sequence between decision rules and policy values which approach the optimality.

In general, policy iteration algorithm is believed to have less iterations before achieving optimality than value iteration algorithm while each iteration usually takes longer to finish.

3. Linear Programming:

Linear programming is a third method to solve a Markov decision process problem, especially for the problem with additional constraints. The basic idea is to translate the MDP problem to a LP problem and solve it with efficient LP algorithm.

The main reasons are that there have been efficient algorithms to solve an LP problem and when there are additional constraints in the model, the other two methods become infeasible. However, when the state space gets larger, the number of constraints in the LP problem is larger which increases the complexity.

4.3.3 Model Assumptions

The major model formulation assumptions are as follows:

1. Traditionally, the life of a product is divided into multiple lifecycle phases or stages. Variations of this sequence have been described in product development literature and have been found to be valid across a diverse range of products and environments [107,108,109]. In this paper, we establish five product lifecycle phases as shown in Figure below.

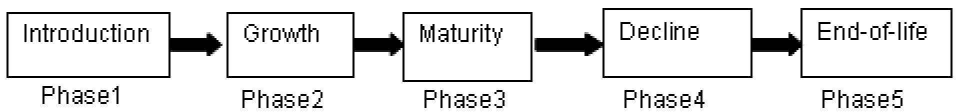

Figure 12 Product Lifecycle Phases

2. Each of the M products is independent of other products from the perspective of company profit making and corporate decision making.

3. The more the company invests in the product, the faster it matures and the slower it declines in the product lifecycle evolution process.

4. Seasonal demand fluctuations and market competition changes are incorporated into the MDP model state so that the system obtains the Markovian property.

5. The probability transition matrix is time-independent, i.e. the transition probability is only based on the state and action, not the decision epoch.

4.3.4 Model Parameters

We formulate this problem as a discrete-time, infinite horizon, discounted Markov decision process model. Here "discrete time" means decisions are not made on a continuous basis; "infinite horizon" formulation is utilized when the end epoch of the decision system cannot be foreseen; "discounted" takes into account the value of time (the profit made tomorrow is worth left than the profit is on hand now).

The key ingredients of this MDP decision model are:

1. A set of decision epochs: $T = \{t_1, t_2, ...\}$. We assume that the products' lifecycle phases, market demands and competition levels are observed, and decisions are made on a periodic basis.

2. A set of system states: $S = \{ s_1, s_{2,} ..., s_L \}$. A system state consists of three elements: the phases of the M products, the market competition, and the monthly demand.

Product phases: each product can be in one of the five lifecycle phases.

Seasonal demand: the market seasonal demand is assumed to be known (by market research).

Market competition: market competition scenarios are categorized into different levels in this model.

To quantify the partition of the market demand, we assign a *Phase_Competition_Index* to each of the *M* products from the company, and also assign a *Market_Index* to the similar/same products from other companies in the market. The demand of a given product is then established in proportion to its *Phase_Competition_Index*.

For example, if the total market demand for the product at a certain decision epoch *t* is *D*, the *Phase_Competition_Indexes* of the *M* products are $PCI_1, PCI_2, \ldots, PCI_M$, and the *Market_Index* of the rest of the market is MI_{Market}, then the market demand share for product *i* is

$$D \cdot PCI_i \Big/ \left(\sum_{j=1}^{M} PCI_j + MI_{Market} \right)$$

A product's competition index is a variable in the system: it increases as the product evolves towards its maturity lifecycle phase, and then decreases as the product declines towards its end-of-life phase. Similarly, MI_{Market} also has some uncertainty and in the lower market competition scenario, the market index of competing products MI_{Market} is smaller than in the higher market competition scenario.

3. A set of available actions can be taken corresponding to each state *s*: $A_s, \forall s \in S$. These actions, which may or may not be the same for different products, include the investment levels of all *M* products at the current month (decision epoch).

4. A set of state and action dependent immediate rewards: $r_t(s,a)$ where $a \in A_s$. The reward is calculated as the sale revenue subtracting investment, i.e., the net profit, of the current month.

5. A set of state and action dependent transition probabilities: $P(j \mid s,a,t)$ where $t \in T$. This is the probability that the system transfers to state *j* in the next month given the current state *s* and the action *a* taken this month.

We assume the probability matrix is time-independent, so $P(j \mid s,a,t)$ becomes $P(j \mid s,a)$. Suppose there are a finite number of actions (investment levels): $a_1, a_2, ..., a_n$, the transition probability matrices corresponding with action a_i is $P(a_i)$:

$$P(a_i) = [p_{ij}]_{|s| \times |s|}$$

where p_{ij} is the transition probability from state *i* to *j*, and $|S|$ is the cardinality of *S*. Then $\sum_j Pij = 1$ is true for every row *i*, where p_{ij} can be determined by statistical analysis for the product.

In the next decision epoch (at time t+1), a product can stay in its current stage state or can also evolve to a new stage state. An end-of-life product is an extinguished product, and its transition to introduction stage state represents the introduction of a new product.

The values of these transitions from phase to phase depend on the lifecycle phases of the products and the investment levels of a company into those products. It is also assumed that the transitions of different products are independent of each other.

The product lifecycle phase transition diagram is shown below in Figure 13. It is assumed that there are only backward transitions at the end-of-life stage where it means that a new product is introduced into the market.

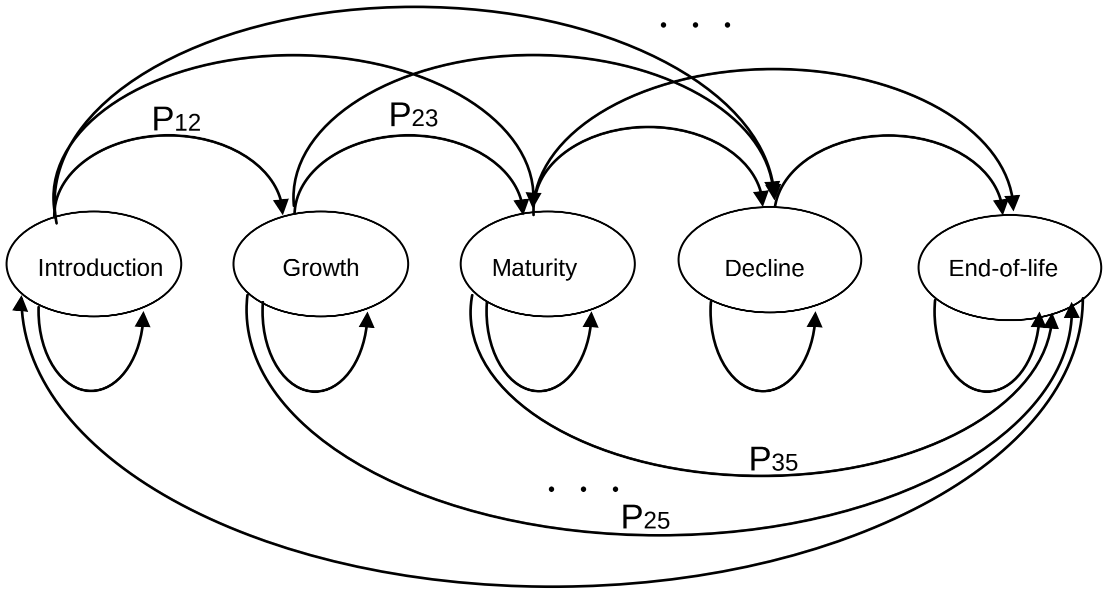

Figure 13 Product Lifecycle Phase Transition Diagram

Market competition: It is assumed that the transitions of market competition levels follow a Markov chain process as shown in Figure 14.

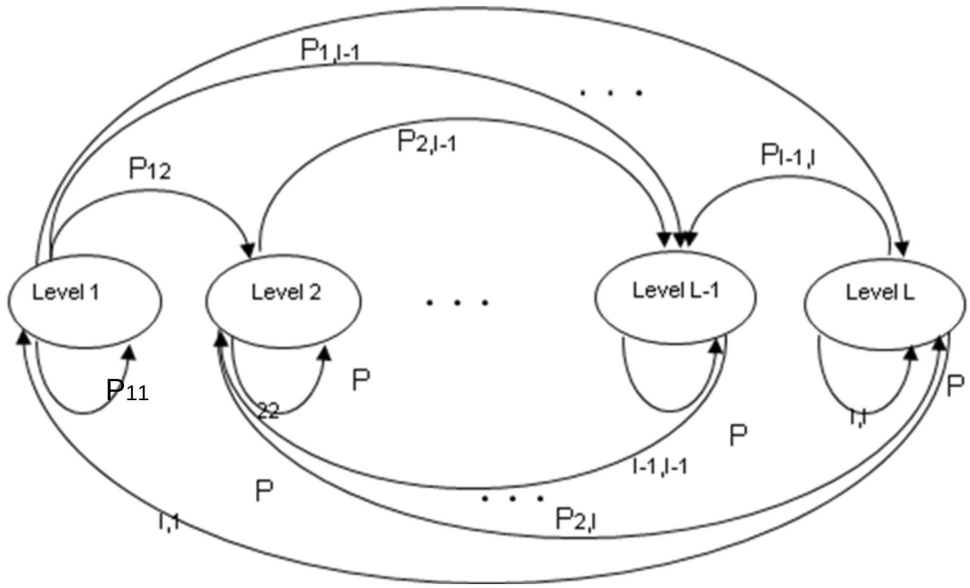

Figure 14 Market Competition Transition Diagram

Seasonal demand: In order to maintain the Markovian property, seasonal demand fluctuations are incorporated into the system states. Thus the transitions of demand follow the chronological sequence.

6. Reward function $r_t(s,a)$ is defined to be the net profit gained after taking action *a* at decision epoch *t* when the company is in state *s*. And $r_t(s,a)$ can be estimated by an economic survey and analysis for a specific industry or company.

7. Objective function: the objective in this model is to maximize the expected discounted total profit from all products over the rest of the time horizon. The long-term discounted profit for the product at state *s* is denoted as $V(s)$.

The optimal solution to this problem can be obtained by solving the following set of recursive equations [103]:

$$V(s) = \max_{a \in A_s} \{r_t(s,a) + \lambda \sum_{j \in s} P(j \mid s,a) V(j)\}, \ s \in S$$

Since this is a discrete time, infinite horizon formulation, there exists a stationary optimal policy for this Markov decision process problem [103].

4.4 COMPUTATIONAL RESULTS AND ANALYSES

Consumer industries ranging from electronics to automobiles introduce style changes or new products on a periodic basis. This is also followed, to a greater degree, in the consumer electronics industry that is characterized by a high degree of competition and an especially short lifecycle.

In this section, we provide numerical examples and analyses in the digital camera market. These results can be extended to other products and industries as well. Data used in the numerical examples is adapted from Canon annual report 2005 and the Canon website (see http://www.usa.canon.com/home).

4.4.1 Further Assumptions

Further assumptions are introduced in this case study for the purpose of demonstration and analysis. However, it should be noted that most of the assumptions can be released by minor adjustments to the model parameters.

1. Assume there is no backward transition except at the end-of-life stage. Backward transition from end-of-life stage to introduction stage implies that a new product is developed, released to the market, and replaces an existing end-of-life product. This assumption states that once the product is released to the market, it has to go through its

lifecycle stages, and cannot transit backwards, e.g., the transitions from maturity phase back to introduction phase are not considered in the model.

2. The lifecycle of each product is sequential with no leapfrogging (skipping intermediate states and jumping to the later state in the lifecycle evolution) between phases. For example, the lifecycle evolution of Canon Powershot A75 cannot jump from introduction phase to the end-of-life phase in the following decision epoch. This can easily be extended by adjusting the decision epoch setup and the transition probability matrices.

The simplified product lifecycle phase transition diagram is shown in figure 15.

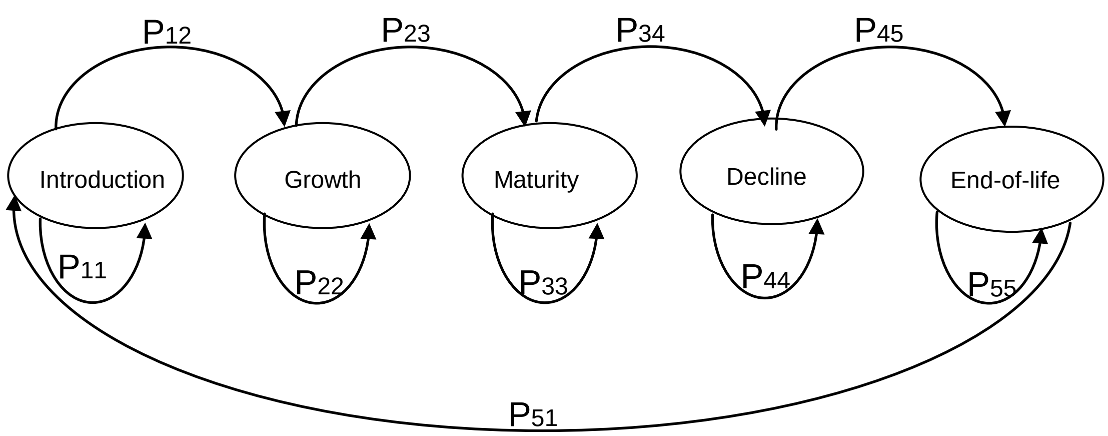

Figure 15 Simplified Product Lifecycle Phase Transition Diagram

3. We assume that the Powershot department in Canon Company produces and markets three digital cameras (Powershot A75, Powershot A80, Powershot A85 [110]). These three types of cameras can be at any of the five lifecycle phases: introduction, growth, maturity, decline and end-of-life.

4. The total market demand varies from month to month, and peaks occur in May (Mother's day), June (Father's day), November (Thanksgiving) and December (Christmas).

5. To simplify the model, we combine the competitive factors from inside and outside the company. In this numerical example, we consider two competitive levels (low and high market competition levels), which can easily be generalized to the *L* level case. It is assumed that market competition is a Markov chain as follows in Figure 16.

At each decision epoch, the market competition can be at high level or low level. It follows a Markov stochastic process, therefore, at the following decision epoch, the market competition can stay the same level or transit to the other level with certain probabilities.

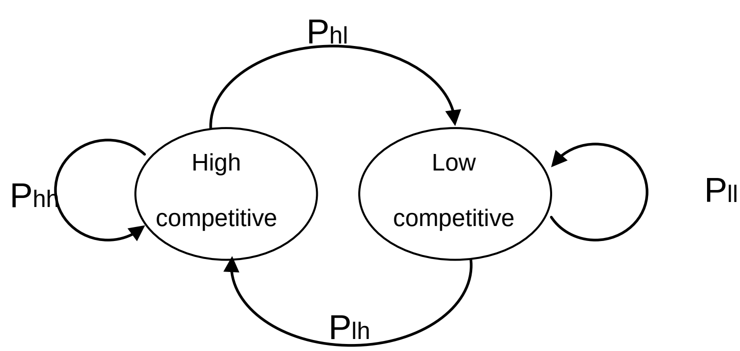

Figure 16 Market Competition Transition Diagram

6. There are three levels of support or investment that the Powershot department can make: $A_s = \{a_1, a_2, a_3\}$. Investments include upgrading the product, repackaging it, initiating a new marketing campaign, and so on.

4.4.2 Numerical Parameters

Decision Epoch T : Say Canon Inc. makes investment decisions on product on a monthly basis.

Therefore the decision epoch T = {January, February, March, April, May, June, July, August, September, October, November, December, …}, for simplification, T = {1, 2, 3,…,12, …}.

State Set S :

- Considering the five lifecycle phases, the total number of possible phase combinations is 5^3, since Canon Inc. keeps 3 types of digital cameras in the market.
- The market competition is categorized into two levels: Low (*L*) and High (*H*) in the numerical example section. Therefore, the number of states becomes $5^3 \times 2$ in the system.
- In addition, we incorporate the monthly demand fluctuations into states in order to maintain the Markovian property, which increases the total number of states to be $5^3 \times 2 \times 12$.

Action A_s : Supports or investments from the Canon Inc. are categorized into three levels. Examples of supports include implementing an advertising campaign to raise awareness of the product, designing a new webpage for products, promotions in the retail stores, cultivation of new distribution channels [111], etc.

In this MDP model, the decisions from the company are referred to as actions that can be taken.

These include:

– provide minimal support for the digital camera: a_1

– provide a medium level of support for the digital camera: a_2

– provide a high level of support for the digital camera: a_3

These decisions will affect the probability transition matrix.

Transition Probability $P(\cdot \mid s,a)$: We make no distinction between the three products (Powershot A75, Powershot A80, Powershot A85) in terms of growth through their product lifecycle. The transition probability matrices for a single product can be estimated from product characteristics and competition in the market. It should be noted that these matrices may vary from product to product and from industry to industry.

In the numerical example, for a single product (Powershot A75, Powershot A80 or Powershot A85), we use:

$$P_{a_1} = \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.95 & 0.05 & 0 & 0 \\ 0 & 0 & 0.85 & 0.15 & 0 \\ 0 & 0 & 0 & 0.85 & 0.15 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \text{ under action } a_1;$$

$$P_{a_2} = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 & 0 \\ 0 & 0.9 & 0.1 & 0 & 0 \\ 0 & 0 & 0.9 & 0.1 & 0 \\ 0 & 0 & 0 & 0.9 & 0.1 \\ 0.9 & 0 & 0 & 0 & 0.1 \end{bmatrix} \text{ under action } a_2;$$

$$P_{a_3} = \begin{bmatrix} 0.88 & 0.12 & 0 & 0 & 0 \\ 0 & 0.88 & 0.12 & 0 & 0 \\ 0 & 0 & 0.92 & 0.08 & 0 \\ 0 & 0 & 0 & 0.92 & 0.08 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \text{ under action } a_3.$$

The nonzero elements in the matrices may not be accurate and can be more accurately estimated by more detailed data. The rationale for the nonzero elements follows the relationship described in the following section and the value is somewhat arbitrary.

The relationship between the three matrices follows the transition relationship under the three types of actions:

- $P_{a_1}(1,2) < P_{a_2}(1,2) < P_{a_3}(1,2)$ and $P_{a_1}(2,3) < P_{a_2}(2,3) < P_{a_3}(2,3)$: this states that the greater the support or investment are for the product, the easier it will transit towards the maturity phase which is assumed to be most profitable for the company.
- $P_{a_1}(3,3) < P_{a_2}(3,3) < P_{a_3}(3,3)$: this implies that the greater the support or investment are for the product, the longer it will stay at the maturity phase which is assumed to be most profitable for the company.
- $P_{a_1}(4,5) > P_{a_2}(4,5) > P_{a_3}(4,5)$: this implies that the greater the support or investment are allocated for the product, the longer it will stay closer to the maturity phase which is assumed to be most profitable for the company.
- $P_{a_1}(5,5) = 1$: this states that with action a_1, the little support or investment provided cannot initiate the process of launching a new product.
- $P_{a_3}(5,5) = 0$: this states that with action a_3, the highest level support or investment will initiate the process of launching a new product right away and the new product will be in the introduction phase at the subsequent decision epoch.

In the case of multiple products, the transition probability matrices are derived from the single product matrices in the following manner:

- Considering the number of products, the dimensions of the matrices is increased from 5×5 to $5^3 \times 5^3$.
- Since the demand is expected to change each month throughout the year, the dimensions of the matrices further increase from $5^3 \times 5^3$ to $(12 \times 5^3) \times (12 \times 5^3)$.
- After taking the competition factor into account [low (*L*) or high (*H*)], the transition probability matrix size becomes $(12 \times 5^3 \times 2) \times (12 \times 5^3 \times 2)$ or 3000×3000.
- The probability element in the multiple product matrices can be derived from corresponding cells in each small 5 × 5 matrix by multiplication. This holds, provided the assumption that products are independent in the corporate decision making process.

Reward $r_t(s,a)$ is defined to be the net profit at state *s* after taking action *a*. The reward function is determined by the market demand, product profitability and action cost:

$$r_t(s,a) = PI(s) \times D(s,t) \times MS(s) - SC(a)$$

where *PI(s)* is profit index, *D(s, t)* is total market demand, *MS(s)* is market share and *SC(a)* is investment support cost, for example advertising or technical investment.

Single product market demand is determined by the total market demand and the market share. *Market_Share* is related to the lifecycle phases that the products are in at the decision making epoch. It must be noted here that the *Phase_Competition_Index* can be estimated from the product lifecycle curve as seen in Figure 17 since it illustrates the relationship between sales level and lifecycle stages [112].

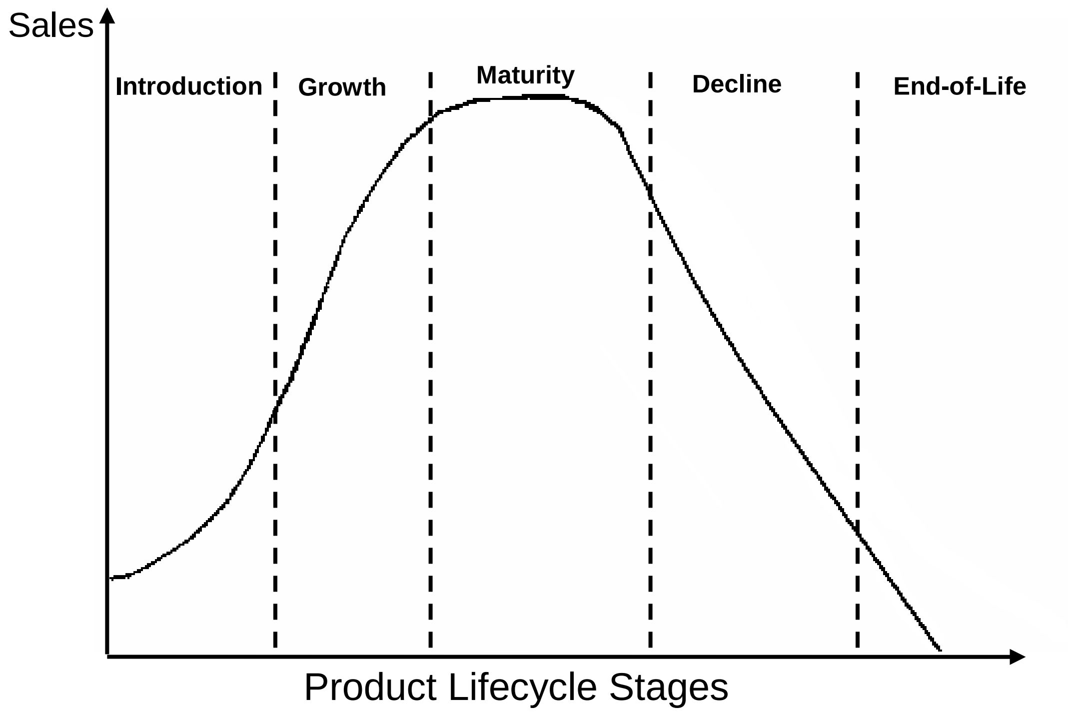

Figure 17 Relation between sales and lifecycle stages

Based on Figure 17, a product will have a greater market share as it gets closer to its maturity phase since the product profitability is bigger. The *Phase_Competitive_Index* will also be correspondingly higher. In the numerical examples, *Phase_Competitive_Index* = [1, 2, 3, 1.5, 0]. This is roughly estimated from the relative sales in each lifecycle phase from figure 17.

Market competitive level is denoted by *Market_Index* = $[L_1, L_2]$. L_1 corresponds to a low competition level, while L_2 correspond to a high competition level. The index correlates positively to market competition.

Profit_Index characterizes the ability to make a profit. This is determined by the lifecycle phase the product is in. For example, at maturity phase, products have higher profit index than other lifecycle stages. We use percentage of the gross revenue to represent *Profit_index*.

Support_Cost is determined by the action taken at the decision epoch. The transition probability matrices are affected by the action.

The objective in this model is to maximize the expected discounted total profit from all products over the rest of the time horizon. The long-term discounted profit for the product at state *s* is denoted as $V(s)$.

A discount rate of $\lambda = 0.95$ [103] is used in the numerical examples. This discount rate considers both the time value of money and the opportunity cost. However, it must be noted that the value of λ varies from industry to industry.

Since the products can be at any lifecycle stages in the process, we take the expected value of the long-term discounted net profit over the state space set S .

4.4.3 Solution Techniques

Policy iteration algorithm [103] is used to solve this MDP problem, basic steps are as follows:

1. Set *n*=0, and select an arbitrary decision rule $d_0 \in D$.

2. (Policy evaluation) Obtain the policy value v^n by solving

$$(I - \lambda P_{d_n})v = r_{d_n}$$

3. (Policy improvement) choose d_{n+1} to satisfy

$$d_{n+1} \in \arg\max_{d \in D} \{r_d + \lambda P_d v^n\}$$

setting $d_{n+1} = d_n$ if possible.

4. If $d_{n+1} = d_n$, stop and set $d^* = d_n$, otherwise increment *n* by 1 and return to step 2.

The algorithm is implemented in Matlab to solve the numerical examples.

4.4.4 Results Analysis

Digital camera industry has its unique properties: seasonal demand fluctuations, short product lifecycles and fierce market competitions. The corporate decisions in the product lifecycle evolution process are essential to the successes of the products.

In the computational analysis section, three scenarios are implemented for model demonstration and validation. We call them the normal (base) case, higher demand case and higher competition case. The normal (base) case serves as the baseline in the analysis. In the higher demand case, the total market demand is increased by 10% in May, June, November and December. In the higher competition case, the market competition index is increased by 20%, which means there is 20% more competition from similar/same products in the market.

The reasons to choose theses scenarios are: (a) for the purpose of comparison and demonstration; (b) market demand and competition are the two major factors which affect the product decision making in the digital camera market.

Normal (Base) Scenario Analysis:

For each scenario, we investigate the monthly optimal decisions throughout the year. Figure 18 demonstrates the normal (base) case. For demonstration purpose, the states are compressed in the figure. The three products can be at any of the five lifecycle phases and in the figure investment decisions are averaged over the product lifecycle phase subspace. It shows the total market demand, company's investment on product combination and the corresponding expected discounted total profit in the base scenario. The left half is the scenario with market competition level L (MI_{Market} = 20) and the right half of the figure is the scenario with market competition level *H* (MI_{Market} = 30).

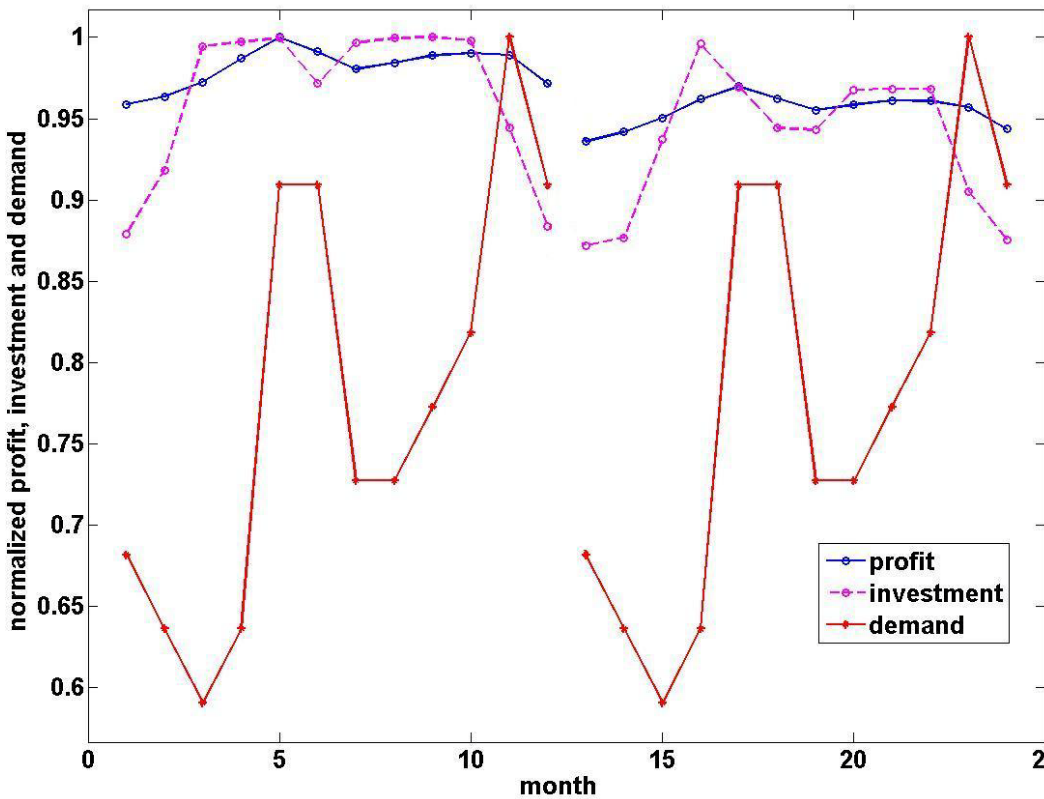

Figure 18 Profits, Investment and Demand for Base Scenario

As we can see from the Figure 18, optimal decisions are usually far-sighted. The market demand is at its peak in May, June, November and December. Based on the model output, the large investment action should be taken in April and October in order to get the company be prepared for the coming high demand. If the company forecasts the high demand in June and provides large investment in June, the products typically do not have enough time to grow to maturity in order to meet the high demand.

Investment Action vs. Product Lifecycle Phase:

In the numerical example, we also investigate the relationship between the investment actions and the product lifecycle phase. In this part of analysis, the factors of market competitions and demand fluctuations are not considered. Therefore, the results that are demonstrated below in Figure 19 are averaged over those two factors.

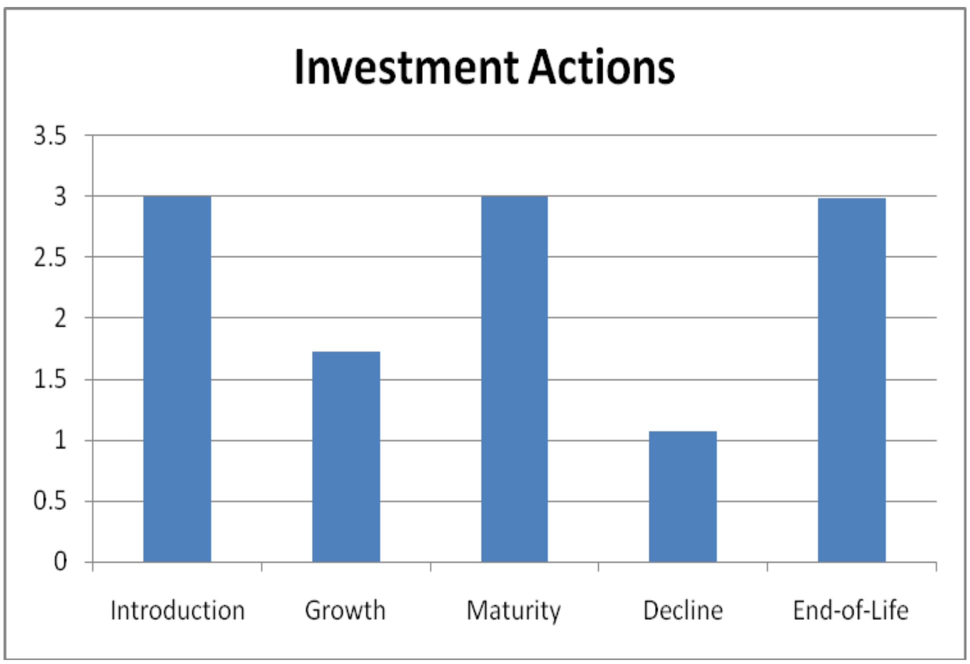

Figure 19 Investment actions vs. Product lifecycle phases

As we can see from the figure, when a product is at its introduction phase, a high support level is recommended. A company wants to give the products a large accelerate to grow as quickly as possible to the maturity lifecycle phase, which means more profit can be generated by the product.

From the computational output, a medium investment/support action is recommended at the growth phase. The rationale is that every product needs sometime to be tested by the market. The medium investment level can better help separate the high potential products from those with low potential. And when a product is at its maturity phase, the company may want to invest most as well. In this way, this product can remain in its maturity phase for a longer period of time.

We find that when a product is at its decline phase, the company should consider providing low or no investment support. The company should just let the product evolve through its product lifecycle, since it may not be worthwhile to invest large amount of money/efforts for a declining product. Because of the capacity constraint of keeping M types of products in market, the company can make more profit out of products that are in their maturity phase.

When a product is at its end-of-life stage, the company should consider making a significant investment. The rationale is that the company has the ability to maintain a certain amount (M) of products, and it should utilize the capacity to the maximum in order to make great profits.

Profit Comparison and Analysis for Three Scenarios:

Profit is the major factor to affect company's decision making. Therefore, we investigate the model sensitivity of profit to demand change and competition change by comparing with the profit of the three scenarios, as shown in Figure 20. Similar as in Figure 18, the left half is also the scenario with market competition level L (MI_{Market} = 20) and the right half of the figure is also the scenario with market competition level *H* (MI_{Market} = 30).

As is shown below, at higher demand case, the total profit is increased compared to the normal case and at higher competition the total profit decreases. These results match the common economic sense very well, which verifies the MDP model.

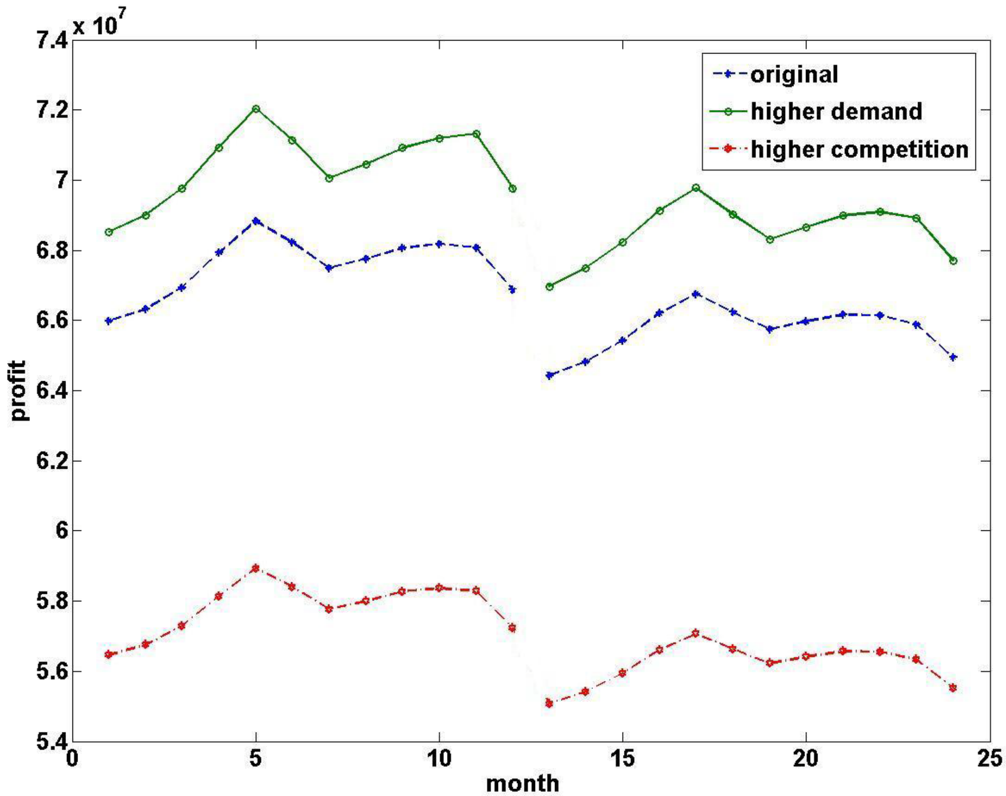

Figure 20 Comparisons in Profit in Three Scenarios

Investment Decision Comparison and Analysis for Three Scenarios:

We investigate the investment change sensitivity when the market demand and competition level change as shown in Figure 21. The left half is the scenario with market competition level L (MI_{Market} = 20), and the right half of the figure is the scenario with market competition level H (MI_{Market} = 30).

It is observed that at higher market demand case, the investment in April and October increase a lot. It also states that optimal action is usually made far-sighted. At the higher competition case, the investment decreases. This observation is also reasonable. This is due to the fact that the market share for a single product will decrease because of higher market competition, and the company does not need to invest much money.

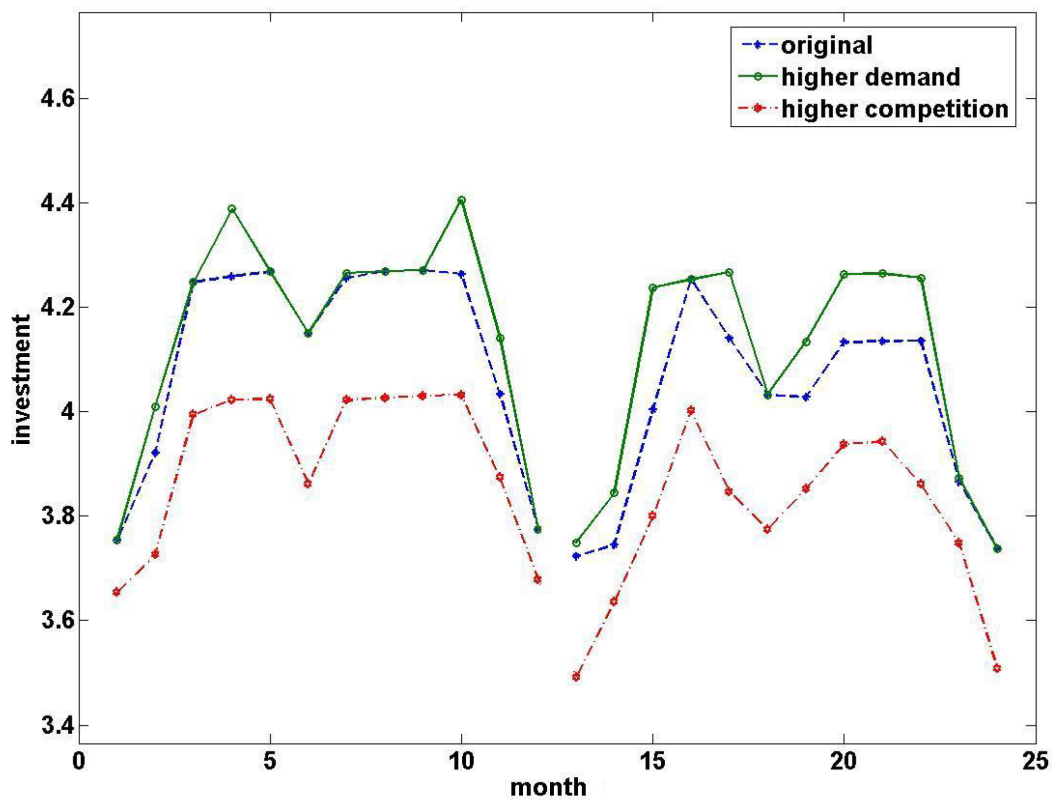

Figure 21 Comparisons in Optimal Investment Action in Three Scenarios

In summary, this model output matches the real industry decision making strategy and common sense. This verifies the MDP model. In addition, this model can provide a more detailed decision making scheme.

4.5 CONCLUSIONS

In this chapter, Markov decision process methodology is used to model sequential decision making problem in product lifecycle management arena.

The major findings are as follows:

1. Corporate decisions should be made with a far-sighted approach. For example, the demand forecasts for May and November are higher while the optimal policy from the MDP model suggests that the company investments in April and October should increase significantly to be prepared for the expected demand increase.

2. When the market is more competitive, the company should decrease its investment and vice versa. This is due to the fact that the market share for a single product will decrease because of higher market competition, and the company does not need to invest much money.

3. When the market demand is lower, the company should decrease its investment and vice versa. This is because that the market share for a single product will decrease accordingly with the decrease of demand for the whole market, and the company does not need to invest much money.

4. When a product is at its introduction phase, high investment support is recommended. A company wants to keep products as close to maturity as possible, which means more profits can be made from the product.

5. When a product is at its maturity phase, the company may want to invest the most as well. In this way, this product can remain in its maturity phase for a longer period of time, which translates to greater profitability of the company.

6. When a product is at its decline phase, the company should consider providing low or no investment support. The company should just let the product evolve through its product lifecycle, since it may not be worthwhile to invest large amount of money/efforts for a declining product.

7. When a product is at its end-of-life stage, the company should consider making a significant investment. By investing at this stage, new products can be introduced to the market and maintain competitive edge.

The numerical examples suggest consistency between the model conclusions and corporate decision making common sense. This validates the MDP model formulation, and with this MDP model formulation, more detailed and informative guidelines can be provided for the company decision makers.

The major contribution of this study is the application of Markov Decision Process methodology in the lifecycle evolution analysis. It is a general model formulation that can be adapted for a multitude of industries and products. In addition, for future research direction, reverse logistics concept can also be incorporated into the model for decision making in closed-loop supply chain management systems, and detailed information is introduced in section 5.3.3.

5.0 SUMMARY AND CONCLUSIONS

This dissertation addresses sustainability issues in the engineering arena. Three interrelated problems are studied in this dissertation: waste reduction in manufacturing, green product deployment strategies and product upgrade decision making. Mathematical models for each of these problems are developed to assist various stakeholders in making the rational decisions at corresponding product lifecycle stages.

The linkage between these segments loosely follows the evolution of the product through its lifecycle. Validations are carried out based on data either from real industrial applications or from the public domain.

5.1 RESEACH SUMMARY

The research carried out in this dissertation study is summarized in this section. Three interrelated research problems are studied to assist decision making for various stakeholders from the perspective of sustainability.

5.1.1 Project Portfolio Selection to Implement Lean and Six Sigma Manufacturing

The first part of this research focuses on identifying the optimal decisions in waste reduction in the product manufacturing phase.

The application of Lean and Six Sigma has made a significant impact both in academic and industrial area over the last decade. One of the complex decisions in lean and waste reduction is the project portfolio selection with a limited amount of available resources.

A multi-objective decision making model with Pareto frontier chart is developed. This will help decision makers identify the optimal project portfolio for implementation of Lean and Six Sigma concepts. The mathematical model is also validated by industrial data from a mid-sized semi-conductor company. This model can be extended to other industrial applications where trade-off decisions have to be made between multiple objectives.

5.1.2 Game Theoretical Models for Market Competition Analysis in Green Production

The second segment of this research concentrates on the market competition analysis between green and ordinary products.

As global awareness and concern for the environment increase, many policy makers, stakeholders and business leaders have begun to call on the business community to play a major role in moving the global economy development toward sustainable development.

Market competitiveness is an important factor for corporate strategic decision making. In this part of the research, game theoretic models are developed to analyze the market competition. The dynamic equilibrium is also studied as companies enter and leave the market. A sensitivity analysis is conducted to analyze the factors for the healthy growth of green products in a competitive market.

This game theoretic model can provide engineering and managerial insights on how to help green production to survive in the fierce market competition. In addition, the effects of the government and regulatory organizations interventions are considered, such as tax reduction/subsidy for green products, standard on carbon dioxide emission and education for public awareness.

5.1.3 Long Term Profit-driven Decision Making in Product Market Lifecycle Management

The last part of this research focuses on identifying the best investment decision at each phase of a product's lifecycle after it has been released to the market. This is one of the key elements in product upgrade and marketing strategies.

This mathematical model considers a sequential decision making process through each stage of the product lifecycle after its release to the competitive market. This problem is formulated as a Markov decision process (MDP) model where optimal sequential investment decisions are made based on the product lifecycle phases and market demand fluctuations so as to maximize the long-term profit.

In summary, this dissertation study concentrates on developing and validating mathematical models of the product lifecycle decision making in the context of sustainability. There are three interrelated parts of this research and the linkage between these segments loosely follows the evolution of the product through its whole lifecycle. Industrial case studies are utilized to validate the mathematical models and develop guidelines for strategic decision making for manufacturing corporations. This study contributes to the body of knowledge in decision making for manufacturing companies by developing novel, validated, quantitative models for decision making through a product's lifecycle.

5.2 RESEARCH CONCLUSIONS

The research conclusions drawn from this dissertation study is summarized in this section. Three subsections correspond with each of the three interrelated research problems: waste reduction in manufacturing, green product deployment strategies and product upgrade decision making. The objective for this dissertation study is to assist decision making for various stakeholders from the perspective of sustainability.

5.2.1 Project Portfolio Selection to Implement Lean and Six Sigma Manufacturing

This part of the dissertation study considers a project portfolio selection problem in order to implement the Lean and Six Sigma concepts. A Multi-objective model is formulated to approach the problem and Pareto frontier chart is developed to assist decision makers. The industrial case study validates this decision support system.

The major findings are summarized as follows:

1. It is appropriate to utilize the multi-objective formulation to effectively solve the project portfolio selection problem in the Lean and Six Sigma implementation process.

This can be used to provide quantitative support to the corporate executives when they make the decisions on project portfolio selection.

2. A decision support system based on the multi-objective mathematical model provides the flexibility of adjusting the weight of multiple objectives in the decision making process thanks to the property of Pareto frontier set.

3. The probability of choosing a project does not monotonically decrease with the increase in the project implementation cost and decrease in the potential benefit from the project. This is due to the additional constraints included in the realistic model formulation, such as diversity constraints and management limit constraints.

4. The integrated benefit objective function considers the interaction between projects in the process of implementation. The concept of probability of parallel systems can be adopted to address this issue.

5. It is necessary and appropriate to simplify the objective function for the overall benefits for project portfolio implementation. This makes the model computationally solvable.

In summary, this multi-objective decision-making model can provide assistance to corporate executives to identify the optimal project portfolio flexibly for Lean and Six Sigma deployment. In addition, this decision support system based on the multi-objective model has the flexibility of being applied to other portfolio selection problems.

The major contribution of this study is objective function formulation. In the multi-objective model formulation, a novel way of defining the objective function for integrated benefit is developed. In addition, the simplification of the objective function for integrated benefit makes the mathematical programming solvable. This model formulation provides a new and better mechanism for project portfolio selection.

5.2.2 Game Theoretical Models for Market Competition Analysis in Green Production

In this part of my dissertation, game theoretic models are formulated to study the competition between ordinary and green companies/company sectors which produce the same type of products with different techniques and costs.

The Nash equilibrium as well as the dynamic equilibrium under the free entry/exit assumption is obtained. Sensitivity analysis is also used to study the possible actions that could be taken to help increase the market share of green products in the market. These results are demonstrated with numerical examples.

In model formulation (A), companies are divided into two types: green companies which produce green products and ordinary companies which produce ordinary products. Each company independently and simultaneously determines their supply quantities in order to maximize their own profits. The competition among them is assumed to be Cournot. The engineering and managerial insights are summarized as follows.

Engineering and Managerial Insights:

1. Green companies need to distinguish their products from ordinary ones to survive in the market.
2. Public awareness of the advantage of green products is important for the healthy growth of green companies.
3. Subsidy/tax reduction could dramatically help increase the market share of green products in the market.

In model formulation (B), each company is assumed to produce both ordinary and green products. We call them “hybrid” companies. Same as in model formulation (A), each company independently and simultaneously determines their supply quantities in order to maximize their own profits. The competition among them is also assumed to be Cournot. The engineering and managerial insights are summarized as follows.

Engineering and Managerial Insights:

1. Green production sectors need to distinguish their green products from ordinary ones to survive in the market.
2. Public awareness of the advantage of green products is important for the healthy growth of green sectors in the companies.
3. Subsidy/tax reduction could dramatically help increase the market share of green products in the market.

In summary, no matter the manufacturer is a pure green production company or one production sector in a hybrid company, the conclusions are similar. To distinguish green products from their ordinary counterparts, to increase public awareness and to impose tax benefits are among the effective policies/methods to better help green production industry survive and thrive in the fierce market competition.

5.2.3 Long Term Profit-driven Decision Making in Product Market Lifecycle Management

In the last part of dissertation, Markov decision process methodology is used to model sequential decision making problem in product lifecycle management arena.

The major findings are as follows:

1. Corporate decisions should be made far-sighted. For example, the demand forecasts for May and November are higher while the optimal policy from the MDP model suggests that the company investments in April and October should increase a lot to be prepared for the coming demand increase.
2. When the market is more competitive, the company should decrease its investment and vice versa. This is due to the fact that the market share for a single product will decrease because of higher market competition, and the company does not need to invest much money.
3. When the market demand is lower, the company should decrease its investment and vice versa. This is because that the market share for a single product will decrease accordingly with the decrease of demand for the whole market, and the company does not need to invest much money.
4. When a product is at its introduction phase, high investment support is recommended. A company wants to keep products as close to maturity as possible, which means more profit can be made by the product.
5. When a product is at its maturity phase, the company may want to invest most as well. By this means, this product can remain in its maturity phase for a longer period of time, which is good for profitability of the company.

6. When a product is at its decline phase, the company should consider providing low or no investment support. The company should just let the product evolve through its product lifecycle, since it may not be worthwhile to invest large amount of efforts for a declining product.

7. When a product is at its end-of-life stage, the company should consider making a significant investment. By investing at this stage, new products will be introduced to the market and maintain competitive edges.

The numerical examples suggest consistency between the model conclusions and corporate decision making common sense. This validates the MDP model formulation, and with this model detailed and informative guidelines can be provided for the company decision makers. It is a general model that can be adapted for a multitude of other industries and products. Reverse logistics concept can also be incorporated into the model for decision making in closed-loop supply chain management.

5.3 FUTURE RESEARCH DIRECTIONS

In this section, future research directions are discussed for each of the three problems: waste reduction in manufacturing, green product deployment strategies and product upgrade decision making.

5.3.1 Project Portfolio Selection to Implement Lean and Six Sigma Manufacturing

In the first part of this dissertation, we consider a project portfolio selection problem in order to implement the Lean and Six Sigma concepts. A Multi-objective model is formulated to approach the problem and Pareto frontier chart is developed to assist decision makers. The industrial case study validates this decision support system.

The research can be extended in the following aspects:

- This model can be applied to other project portfolio selection problems. For example, manufacturing companies which still utilize the rank and choose method for project selection can adopt this model formulation to improve project portfolio selection process.
- We can consider more factors in the model formulation. This is equivalent to including more constraints in the model. For example, in addition to budget constraints, management group and engineering group constraints, we can also include other resource constraints in the model formulation.
- We can try other project objective function simplification methods. Further studies can be conducted on the equivalence on the simplification of the objective functions. For example, we can consider other alternatives for objective function simplifications and possibly use real application example for validation.

5.3.2 Game Theoretical Models for Market Competition Analysis in Green Production

The second segment of this research concentrates on the market analysis for green products. Game theoretic models are formulated to study the competition between ordinary and green companies/company sectors which produce the same type of products with different techniques and costs.

The Nash equilibrium as well as the dynamic equilibrium under the free entry assumption is obtained. Sensitivity analysis is also used to study the possible actions that could be taken to help increase the market share of green products in the market.

Future research can be conducted in the following manners:

- In this study, we conducted research on the general concept of tax benefits and how the benefits can affect green production industry. For future research, we can compare different real world policies. For example, one extension of this study is: we can compare the effectiveness of tax deductions vs. subsidies for green production companies/consumers.
- In the model validation section, the majority of the data is from real world application. However, it would be better if we can conduct a case study either with a focus group of consumers or with green production companies.
- If a real world case study can be conducted, more specific and straightforward guidelines for decision makers can be derived.

5.3.3 Long Term Profit-driven Decision Making in Product Market Lifecycle Management

In the last part of dissertation, Markov decision process methodology is used to model sequential decision making problem in product lifecycle management arena.

The research study can be extended in the following aspects:

- We can incorporate reverse logistics concept into modeling. A typical logistical system follows the following path in Figure 22 which is typically open-loop.

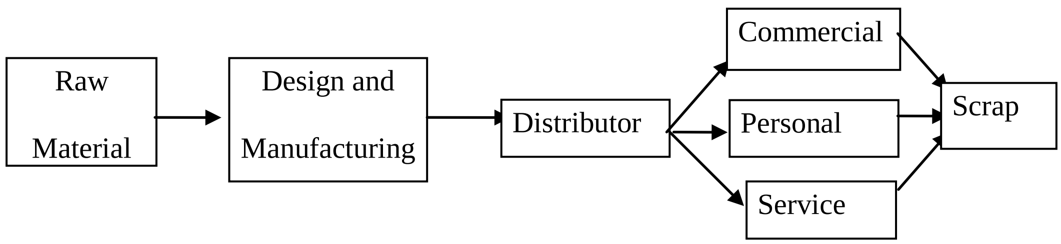

Figure 22 Open-loop logistics system

In recent times, the '3R: reduce, reuse, and recycle' process is gradually being accepted. Manufacturing companies are also starting to adopt the closed-loop logistics system displayed in Figure 23.

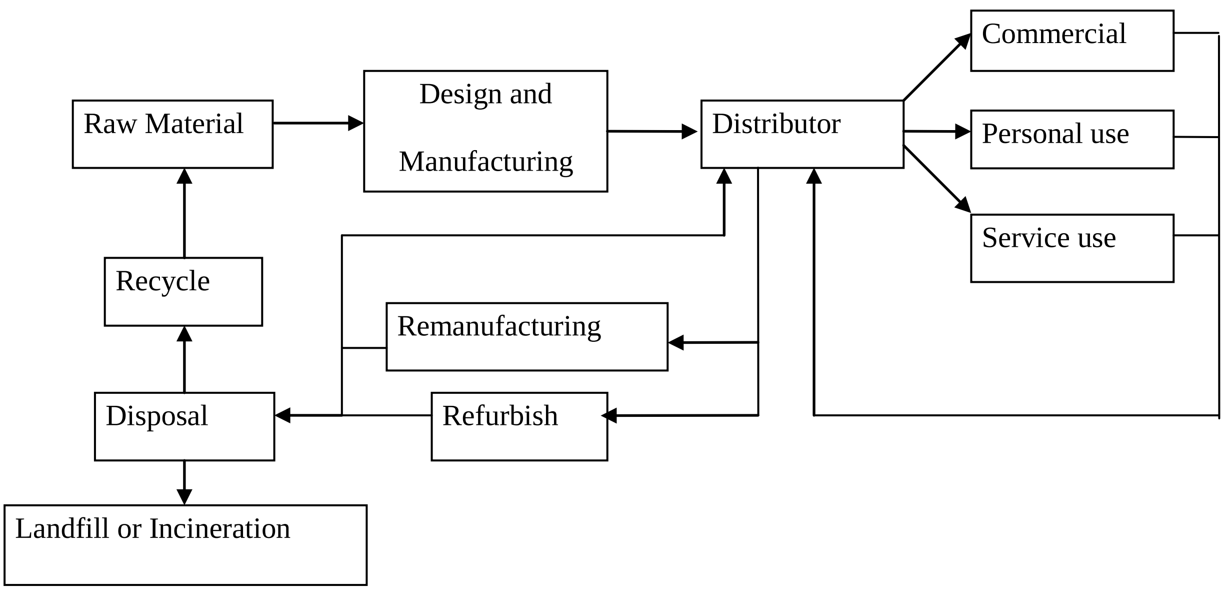

Figure 23 Closed-loop logistics system

In the model formulation, at the end-of-life lifecycle phase, the action space can be extended to {reuse, recycle, and discard} instead of investment support levels.

- Real world case study can be conducted to better validate model and provide specific engineering and managerial suggestions.
- As for solving the mathematical programming problem, it takes days to run the program now. We can explore the possibilities of developing more efficient algorithms to save program running time.

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