Profit Analysis of Green Products in New Product Development

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Abstract

Profit Analysis of Green Products in New Product Development Process

Mohammad Reza Gholizadeh Toochaei

The increasingly negative effects of product development and manufacture on the environment are pushing firms to move towards producing new generations of products, i.e. green products. However, the financial effect of green products in the future is a main concern for managers in charge of new product development (NPD) projects. This research focuses on profit analysis of a new product, which is designed based on recyclability, environmentally friendly disposal, and an energy and emission efficiency strategy, in order to equip decision makers with a proper forecast of profitability of such green new products. In this research, first, a primary mixed integer model is proposed to assess the trade-off analysis of green products based on the Cost Volume Profit model in a life-cycle framework. Then, the model is developed based on dynamic programming and a quantitative choice model is applied in the automotive industry. Finally, two numerical examples are used to evaluate the models. The results show the interaction between profitability and environment-friendly attributes of products based on recyclability, disassembly, and an environmentally friendly disposal strategy. It also provides a decision support methodology for management in order to decide about the future of the project during the business analysis stage of the new product development process.

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I would like to express my deepest appreciation to my mentor and supervisor Professor Nadia Bhuiyan who has taught me how to think about sophisticated issues. I learnt how to perform an applied research, to train engineers through teaching courses, to lead a research group, and to communicate in the scientific environment. Influence of Professor Bhuiyan on my scholarly life is undoubtable and my gratitude and respect for her extends beyond words.

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And now,
"It is better to leave all the science
It is better to hang my heart to tress of my love
Before the faith takes my blood
It is better to pour the blood of grapes into the bowl"

Kayyam Neishaboori

M. Reza Gholizadeh Toochaei
May 2015

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INTRODUCTION

In this chapter, first, a background and basic concepts of the research are reviewed. Then, the objectives and the methodology of the research are discussed. Finally, the outline of the thesis is provided in the last section.

1.1 Background

The environmental impact of products can negatively affect human, animal, and plant life. Resource depletion, greenhouse gases and emissions, climate change, etc. are the most popular evidence that show the effect of products on human health. In 2012, The World Bank reported an annual increase of municipal solid waste (MSW) from 2.9 to about 3 billion tonnes per year through 2002 to 2012 generated by urban residents. This report also estimated that by 2025, MSW will likely increase to 4.3 billion tonnes per year (Hoornweg & Bhada-Tata, 2012). Food waste, paper and paperboard, wood, plastics, glass, metals, rubber, leather, textile, and yard trimmings are the most important sources of MSW (EPA, 2012), Also, automobiles, as part of one of the largest industries, are producing much waste and emission, from the dispersion of toxic particles of brakes and tire debris, painting and coating during production, non-recyclable and polymeric contents, lead-acid of batteries and auto shredder residue in the world every year (EPA, 2014). Additionally, traditional production approaches exacerbate both local and global air pollutions through disposal and landfill of MSW and automobiles, and fossil fuel combustion. Therefore, many laws and legislations have been established by international organizations and governments to protect the environment against pollution that is produced by different sectors. The European Union Emission Trading Scheme (EU ETS), for example, has regulated some targets, known as the 20-20-20 package, to restrict and control manufacturing enterprises' CO_2 emissions and air pollution generation of its country members by 2020 (IEA, 2009). The US Environmental Protection Agency established some standards in order to control local pollution of industries against the occurrence of carboxyhemoglobin levels in human blood associated with health effects of concern (EPA, 2011). These environmental legislations help countries to provide some parameters to define the level of corporate responsibility and accountability of companies (D`Souza, et al., 2006). To address these concerns, manufacturing enterprises have to modify their business or production process in order to be aligned with environmental policies. At the same time, the number of consumers that would rather purchase a 'green' or environmentally friendly product over a comparably priced ordinary product has boosted since 2008 (Savale, et al., 2012). In the automotive industry, for example, the sale of hybrid and electric cars has increased up to 426,000 units in the U.S. at the end of September 2013, 30% greater than the same period in 2012 (Shahan, 2013). Also, car manufacturers expect to sell about 6,000,000 electric cars by 2020 around the world (IEA, 2013). Thus, many companies adopt sustainable practices in their product designs and production processes to increase corporate responsibility, create product differentiation, and grow customer demand for environmentally friendly and energy efficient products (Industry Canada, 2009).

Since 1970, Design for Environment (DFE) has been introduced as a most effective way to minimize environmental impacts, while it can improve products' quality (Ulrich & Eppinger, 2012). DFE is a type of product design that provides a practical method to minimize the environmental impact of a product (Ulrich & Eppinger, 2012; Wang & Gupta, 2011). Today DFE can be applied even on all parts of a product (Wasik, 1996). Therefore, it offers numerous opportunities for manufacturers to fulfill DFE strategies on a part or all parts of the product.

Nevertheless, the product development process is highly uncertain and is a high investment process in many industries (Gerhard, et al., 2008). Thus, manufacturers try to reduce risk and to control uncertainty of implementation of each strategy through financial analysis of a new product in different stages of the development process.

1. 2 New Product Development

Different scholars have proposed different variations of the NPD process (Cooper, 1988; Zirger & Maidique, 1990; Gerhard, Brem, & Voigt, 2008; Ulrich & Eppinger, 2012). According to Booz, Allen, and Hamilton's (1992) classic model, a new product can be developed in seven stages, as illustrated in Figure 1.

Figure 1 Booz, Allen, and Hamilton's classic new product development process model (Booz, et al., 1982)

In the first stage, a company has to define missions and objectives that new products must achieve to satisfy consumers' needs. The second stage of the process is generating a pool of ideas from any potential idea source based on goals and objectives that are determined in the first stage. Screening and Evaluation is the third stage of the new product development process, where an idea generated in the second stage has to be analysed based on its potential contribution to the market. The remaining ideas of stage three have to be assessed in the business analysis stage in order to identify the financial situation of product ideas' launch on the market and decide whether to develop the idea into a new product or not. In the development stage, an idea that successfully met all conditions of previous stages will be transferred into a real world product offering. In this stage, different prototypes are built for laboratory testing and test marketing. Finally, in commercialization, a new product is introduced to the market, while the new product's bugs should quickly be resolved (Booz, et al., 1982).

This process can be divided into predevelopment (strategy, idea generation, screening and evaluation, and business analysis) and development (development, testing and commercialization) (Cooper, 1988). The predevelopment phase has a significant effect on new product success or failure (Cooper, 1988; Booz, et al., 1982). Hence, financial evaluation of a new product has to be done in the predevelopment phase, because after this point it is very difficult and expensive to turn back (Cooper, 1988; Gerhard, Brem, & Voigt, 2008).

1. 3 Business Analysis

Many factors beyond product specifications and performance can affect the product's success on the market (Annacchino, 2003). Sometimes, for instance, consumers struggle to change their behavior towards green purchases. This can occur due to brand loyalty, habit, lack of information, lifestyle, etc. (Young, et al., 2010). Thus, business analysis helps decision makers to identify other associated factors which affect the success of a new product on the market, such as: barriers to entry, current and potential competitors, target markets, market growth information, financial projections, etc., before development begins (Booz, et al., 1982).

As previously mentioned, the business analysis as a last part of predevelopment helps decision makers to assess the capability of ideas, which are selected in the screening and evaluation stage of the NPD process, for translation into viable offerings (Booz, et al., 1982). The purpose of financial projection in business analysis is to clarify the future demand, costs, sales and profitability of the new product for decision makers (Havaldar, 2014). The financial projection of a new product can be broadly categorized into five sections:

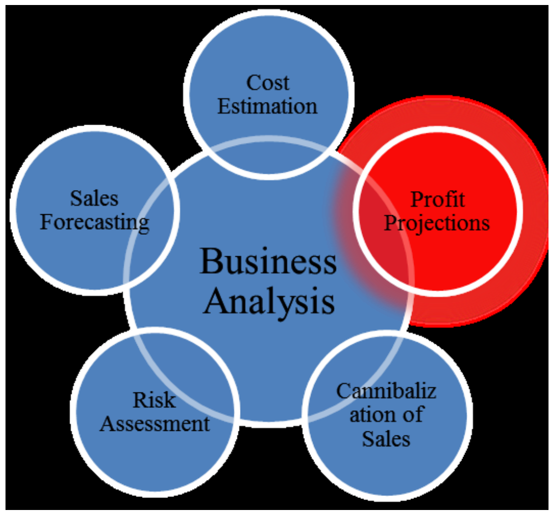


Figure 2 Concepts of financial projection (Barrios & Kenntoft, 2008)

As illustrated in Figure 2, the first step of business analysis is sales forecasting. In sales forecasting, a company estimates total potential market and a new product's demand in each time period. Besides sales forecasting, cannibalization of sales helps decision makers to estimate the degree that the new product can cannibalize the sales of the existing products of the company (Barrios & Kenntoft, 2008). In the next step, companies have to estimate the new product's cost. Cost estimation includes direct costs, investment costs, and overhead costs (Lancaster & Massingham, 2011). Profit projection is another part of the financial analysis that includes break-even analysis. Profit projection is determined based on cost estimation and sales forecasting. Although environmental burdens, competitiveness among companies, and, most importantly, social responsibility could be regarded as significant factors of greening manufactured products among companies (Albino, Balice and Dangelico 2009, Industry Canada 2009), the implementation of DFE strategies need different facilities that affect production factors and product development processes with dissimilar costs for the company. A company's main goal is to define strategies to achieve maximum benefits given threats and opportunities that exist in the related industry. Moreover, profitability of a company is related to its ability to introduce products that are successful on the market (Kumar & Chatterjee , 2013). Thus, different verification methods either through physical tests or numerical calculations are needed to assess the acceptability of a design strategy and compliance with the environment of a new product, as with other products. In this stage, a profit analysis, as an analytical method, helps managers to compare different design approaches based on estimated cost and performance (Fiksel, 2011). Based on this analysis, companies can have a proper forecast of economic effects (profitability) of the project before introducing the products to the market. Eventually, the risk of related to each outcome should be assessed by some techniques and processes (Barrios & Kenntoft, 2008).

1.4 Product Life-Cycle

In a green product, "*life-cycle thinking is the basis of DFE*" (Fiksel, 2011; Ulrich & Eppinger, 2012). The recycling process is a parameter that cannot be considered in the short-term. It takes place at the end of the product life. Thus, the product life cycle analysis, as opposed to a cross-sectional analysis, can provide a proper forecast of associated costs and revenues of the product in the future. Ulrich and Eppinger (2012) proposed a natural life cycle and a product life cycle for sustainable products. The product life cycle consists of extraction and processing of raw materials, production, distribution, use, and recovery of the used product. The natural life cycle, however, represents the effect of each material on nature and reproduction of raw materials after the recovery process. Also, a product's life cycle can be broadly defined based on two cycles, development and physical. Development cycle refers time duration a product is designed and developed, whereas the physical cycle implies a period that the product is tangible, includes production, use, and retirement, as illustrated in Figure 3 (Giudice, et al., 2006).

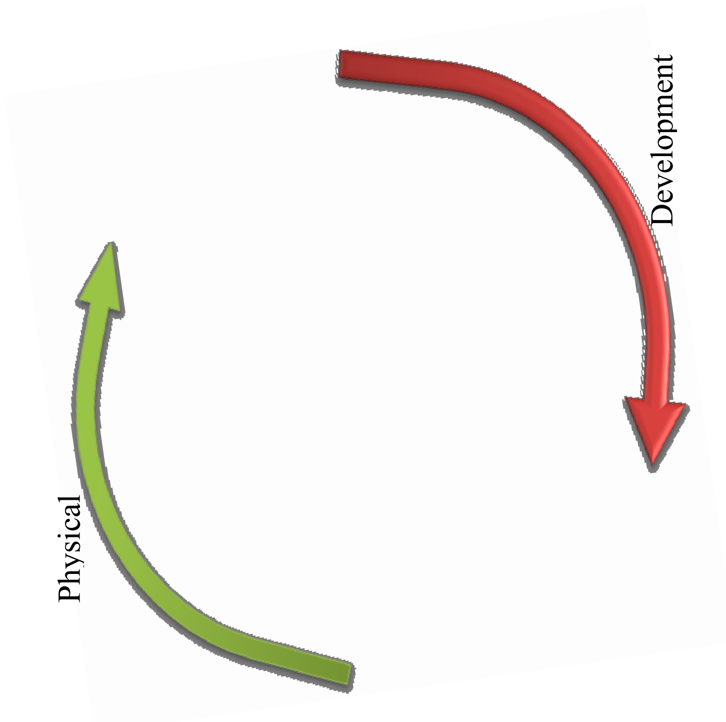


Figure 3 A new product's life-cycle (Giudice, et al., 2006; Vezzoli & Manzini, 2008)

At the end of life cycle, a product or its parts, which are designed according eco-design strategies, can be reused or re-manufactured through a recycling process (Vezzoli & Manzini, 2008). The process of recycling has various benefits and costs for a manufacturer (Chen, et al., 1994). Therefore, missing some critical information about the potential costs and benefits of such products in the business analysis can result in insufficient decisions by managers. Thus, a precise analysis of a product's life-cycle helps managers have a proper forecast of the effect of each new product development project on a company's profit in the future.

1.5 Objectives and Methodology

This research aims to develop a comprehensive model to estimate the profit of a new green product in the business analysis stage of an NPD process. The model presented here is based on design for environment (DFE) strategies of the government of Canada (Industry Canada, 2009) for simple products such as electronic appliances and complex products such as automobiles. In order to achieve this, a dynamic model in terms of a life-cycle framework is proposed

First, DFE principles, goals, and strategies' literature in NPD are reviewed. Second, the trade-off and profit analysis methods of sustainable products are examined and gaps and opportunities, and effective parameters of consumers' demand in green products are identified. Third, DFE strategies and green products' demand are analyzed in order to formulate a green product's related costs and revenues and consumers' demand in the product's life-cycle. Fourth, a mixed integer model is proposed based on deterministic parameters for a simple new green product. Finally, the model is developed based on dynamic programming and qualitative choice models for the automotive industry.

The model is designed based on energy and emission efficiency, recyclability and environmental friendly disposal strategies. In the model, a product's life-cycle costs are broadly divided into four categories: recycling cost, development cost, production cost, and emission tax. The product's revenues are defined in three categories: revenue of used parts, revenue of recycled materials, and sales revenue, in its life-cycle. Then, the model is developed for a dynamic situation and effective parameters of consumers' demand are formulated based on a Generalized Extreme Value (GEV) model.

1.6 Thesis Structure

The research presented in this thesis is organized in four chapters. In the next chapter, the literature on the design for environment and profit analysis of green products is reviewed. In the third chapter, a mixed integer model is proposed for trade-off analysis of new green products. In the fourth chapter, the model is developed based on the Bellman equation and Generalized Extreme Value (GEV) models. Finally, in chapter five, conclusions, limitations, and opportunities for future research are presented.

2. Literature Review

In this chapter, a review of design for environment literature is presented.

2.1 Design for the Environment (DFE)

Firms try to improve their competitive advantage via product innovation to survive in a globally competitive world. The main goal of innovation, based on initial functionality and cost of technology, is to meet demand requirements of consumers or to reduce the price of a product (Adner & Levinthal, 2001). In green products, however, the aim of innovation is reducing environmental impact and improving product performance, which may increase or decrease the price of the product. Nevertheless, companies are trying to produce new products to be either more durable and energy efficient or more recyclable in order to add more value for their consumers through long-term environmental benefits (Wasik, 1996). Since the 1990s, a new type of design for X, called design for the environment (DFE), was proposed by scholars to designers in order to consider their social and environmental responsibilities instead of only commercial interests. In the DFE approach, a systematic practice has been applied by companies to maintain or improve their product's quality while reducing environmental impact (Ulrich & Eppinger, 2012). To achieve this goal, different rules can be defined by a company. In 2006, Luttropp and Lagerstedt recommended *The Ten Golden Rules*, as eco-design guidelines in the process of product development (Luttropp & Lagerstedt, 2006):

1. "Do not use toxic substances and utilize closed loops for necessary but toxic ones.
2. Minimize energy and resource consumption in the production phase and transport through improved housekeeping.

3. Use structural features and high quality materials to minimize weight in products if such choices do not interfere with necessary flexibility, impact strength or other functional priorities.
4. Minimize energy and resource consumption in the usage phase, especially for products with the most significant aspects in the usage phase.
5. Promote repair and upgrading, especially for system-dependent products. (e.g. cell phones, computers and CD players).
6. Promote long life, especially for products with significant environmental aspects outside of the usage phase.
7. Invest in better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear, thereby ensuring reduced maintenance and longer product life.
8. Prearrange upgrading, repair and recycling through access ability, labelling, modules, breaking points and manuals.
9. Promote upgrading, repair and recycling by using few, simple, recycled, not blended materials and no alloys.
10. Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, etc. according to the life cycle scenario."

Also, some authors proposed DFE guidelines based on physical life-cycle stages, as illustrated in Figure 4 (Ulrich & Eppinger, 2012).

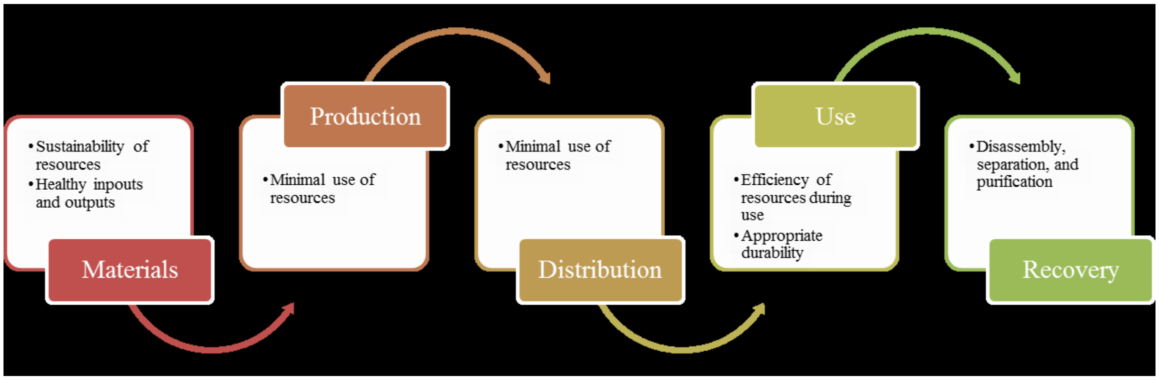


Figure 4 DFE guideline based on a product's life-cycle stage **(Ulrich & Eppinger, 2012)**

Based on such rules, different strategies are proposed to develop environmentally friendly products. Hart (1997) identified three strategies to address environmental sustainability challenges: (1) pollution prevention, (2) product stewardship and (3) clean technology (Albino, et al., 2009). Boons (2002) proposed six options to reduce the ecological impact of a product in product chain management: (1) Material Reduction, (2) Material Substitution, (3) Material Recycling, (4) Product Substitution, (5) Product Recycling, and (6) Eliminate Functions. Fiksel (2011) proposed four principles strategies for DFE, as shown in Table 1.

Table 1 Fiksel's four principal strategies in DFE **(Fiksel, 2011)**

Strategy	Guideline
Design for dematerialization	Design for energy and material conservation
	Design for source reduction
	Design for servicization
Design for detoxification	Design for release reduction
	Design for hazard reduction
	Design for benign waste disposition
Design for revalorization	Design for product recovery
	Design for product disassembly
	Design for recyclability
Design for capital protection & renewal	Design for human capital
	Design for natural capital
	Design for economic capital

Eventually, in 2009, the government of Canada proposed three main strategies of DFE by which North American companies can reduce the environmental impact of their products, as illustrated in Figure 5.

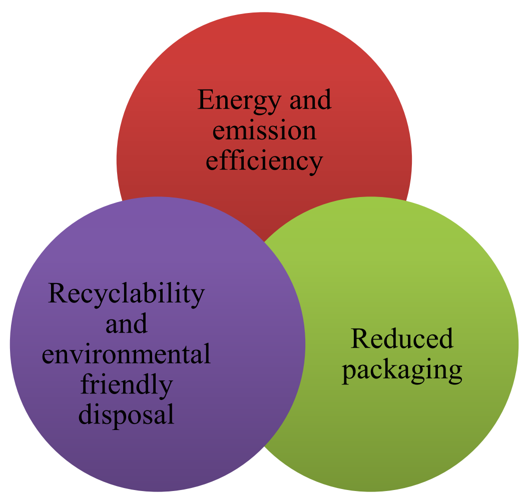


Figure 5 Three main strategies of DFE in North America's industries (Industry Canada, 2009)

Energy and emission efficiency

In 2011, while the use of energy produced 83% of greenhouse gases, 51% of this energy was used by industries worldwide (IEA, 2013). In many countries, governments decided to reduce emissions of products via forcing individuals, businesses, industry and others to pay a part of the cost of negative effects of fuel consumption through a carbon tax (British Columbia, 2014). Carbon price or carbon tax is the amount that must be paid as a tax or the permit cost in exchange for the equivalent CO_2 emission per tonne of greenhouse gases (British Columbia, 2014). The main sources of carbon dioxide emissions in industrial plants are combustion of fossil fuels (e.g. coal, oil and natural gas) and chemical reactions that do not involve combustion (such as reactions in production of metals and mineral products) (EPA, 2014)(Table 2). Additionally, an important indirect effect of industries on the CO_2 emission is the electricity generated in power plants that causes greenhouse gas emission. For instance, the amount of emitted CO_2 in a plant for generating electricity with different fossil fuels, and industrial activities (Table 3) can be estimated accordingly.

Table 2 CO_2 emission by using different fuels in industry (EIA, Environment, 2013)

Fuel	Carbon Dioxide	
Flared natural gas	54.7	Kilograms CO_2
Petroleum coke	102.1	Per Million Btu
Other petroleum & miscellaneous	72.6	

Table 3 CO_2 emission by using different fuels in power plant (EIA, Carbon Dioxide (CO_2) is produced per Kilowatthour, 2014)

Fuel	Carbon Dioxide	
Coal		Kilograms CO_2 Per kWh
Bituminous	0.94	
Sub-bituminous	0.98	
Lignite	0.99	
Natural gas	0.55	
Distillate Oil (No. 2)	0.76	
Residual Oil (No. 6)	0.82	

Therefore, many manufacturers, in order to decrease a part of their production costs, the carbon tax, changed their production process based on energy efficiency or introduced a new generation of products, as for example, hybrid and electronic cars, with optimum energy consumption, to markets.

Recyclability and environmental friendly disposal

Recyclability and environmentally friendly disposal is a main strategy of consumer goods products (CPG) firms and automotive companies in North America (Industry Canada, 2009). The main purpose of recycling is to use materials and components of returned products (Krikke, et al., 1998). At end of a product's life cycle, a product can be recovered via direct reuse, repair, remanufacturing, recycling, or incineration and landfilling process (Wang & Gupta, 2011). Design for disassembly (DFD) is the basis of recyclability (Lambert & Gupta, 2005). Therefore, optimum disassembly based on DFD principles, the selection and use of materials, the design of components and the product architecture, and the selection and use of joints, connectors and fasteners, are important factors in success of this strategy (Industry Canada, 2009).

Reduced packaging

Companies try to reduce their logistics cost, save energy and raw material through more efficient packaging or right planning of the packaging system and production procedure (Zabaniotou and Kassidi, 2003; Industry Canada, 2009). Different strategies of green packaging can be applied by a company to provide a win-win situation for both the company and society/environment, as shown in Table 4.

Table 4 Packaging strategy and related benefits for a company and environment (Verghese & Lewis, 2012)

Strategy	Benefit for Company	Benefit for Environment
Light weighting	Reduced purchase of packaging materials and transportation costs	Benefits through reducing energy and emissions of packaging production and waste transport in a product's life-cycle
Returnable transport packaging	Avoided costs of balling and recycling single-use packaging	Benefit by avoiding over production and waste of single-use packaging in a product's life-cycle
Design for recycling	Reducing packaging components and inventory costs through reducing complexity of the design	Benefit through replacing recycled materials with virgin materials in production of a product's package

Previous Research

In the business analysis phase, portfolio theories in finance, operations research and strategy help management to identify optimal criteria to select from generated ideas (Loch & Kavadias, 2008).

These concepts are used by many scholars for analyzing the financial situation of NPD projects. Chao, Kavadias, and Gaimon (2009) proposed a dynamic model to allocate resources to NPD programs in a portfolio with a focus on how funding authorities and incentives affect a manager's decisions. Kleber (2006) introduced a dynamic model for assessing the financial impact of investment decisions regarding product recovery based on product life cycle and a returns availability cycle. Also, Repenning (2000) developed a dynamic model for the allocation of resources between current and future projects in multi-project development environment. These papers focused on either different aspects of portfolio theories that affect managers' decisions or individual product performance, such as: sales, profit, development cost, and production cost, in business analysis of NPD projects. A development project's success, however, is related to portfolio decisions, such as resource allocation (Loch & Kavadias, 2008), analysis of individual product performance, such as cost saving (Adner & Levinthal, 2001), and many different performance determinants; such as: barriers to entry, current and potential competitors, target markets, market growth information, etc. (Booz, et al., 1982). Also, many scholars focused on profit analysis of green products based on the level of production. Chen, Navin-Chandra, and Prinz (1994) proposed a Cost-Volume-Profit (C-V-P) model of recycling to assess the balance between costs and revenues of disassembly and recycling of a product. Also, Tsai et al. (2012) developed a mathematical model for a green product mix decision based on activity-based costing to evaluate the benefits of expanding various types of capacity. The paper focused on traditional manufacturing costs (machine, labour, and material) and piecewise CO_2 emission cost as the main parameters of a green product mix decision. Raz, Druehl, and Blass (2013) proposed an analytical model to find the production quantity of products which should be designed for the environment, based on the newsvendor model. It focuses on eco-efficient innovations in the manufacturing stage and demand-enhancing innovations. These studies only focused on a particular stage of a product's life while, as mentioned before, life-cycle thinking needs to be the basis of DFE (Ulrich & Eppinger, 2012). Many studies have focused on Life-Cycle Cost (LCC) approaches (Ribeiro, Peças, & Henriques, 2013; Kirkham, 2005; Asselin-Balençon & Jolliet , 2014; Krozer, 2008); however they attempt to introduce different methodologies to estimate a product cost at different stages of the product life-cycle, but do not give attention to how life-cycle approaches can be useful for decision makers to assess optimum production levels for maximizing the profit of the company in all stages of the product life-cycle.

2.2 Summary

In sustainable products, which are designed based on DFE strategies, different hidden costs and revenues have to be considered in profit analysis. Previous studies mostly focused on production costs and sales revenue of products in the business analysis of a new product. All the hidden costs and revenues can affect the decision of decision makers about the future of a new product development project. Also, these studies do not provide a comprehensive model to evaluate the effect of different parameters (number of products produced and recycled, demand for green products) on a green product's profitability. Although each of these parameters is investigated in separate research, there is a gap in better understanding their combined effect on the net profit of a company.

This thesis focuses on the profit analysis of green products based on life-cycle framework to answer some critical questions for helping decision makers to estimate the profitability of a new product which is designed for the environment. Some of these questions include: How many products should be produced based on market demand at a given period in the future? How many of the products sold have to be recycled by the company in future periods when a product is designed based on a recyclability and environmentally friendly disposal strategy? What is the effect of these decisions on the company's profit in the future? The model presented in this thesis pays specific attention to the economic impact of a newly designed product upon related environmental parameters, such as: energy consumption, recycling cost and revenue, and carbon price which is the amount paid to the government as a tax due to statutory regulations. Thus, management can decide about the future of their new products based on the results of the trade-off analysis. In sum, the primary model can determine how many products should be produced and how many of them should be recycled in order to maximize the profit of the companies with employ the potential costs and benefits of recyclability, disassembly, and environmentally friendly disposal strategy. Then, the developed model considers the effect of portfolio decisions, individual product performance and other performance determinants together in order to improve the reliability of the decisions in the profit analysis of a new green product.

3. Trade-off Analysis of Green Products Based on Life-Cycle Thinking

In the trade-off analysis process of new products, five basic cash flows can be defined (Chase, et al., 2006): (1) Development cost, (2) Ramp-up cost, (3) Marketing cost, (4) Production cost, and (5) Sales revenue. In the life cycle approach, however, costs and revenues of a product life cycle can occur in three phases; development, use, and recycling or reprocessing. Development includes production, sales, and the product development process, while use and recycling phases, as a subsequent cost, include recycling cost (Niemann, et al., 2009). Our model focuses on the development and recycling phases. The related costs of these phases can be broadly divided into three categories: Product Development Process Cost, Production Cost, and Recycling Cost. Analogous to costs, revenues also can be allocated via product sale and used parts and recycled materials in the recycling process.

Furthermore, the main effect of the implementation of the recycling process in the product life cycle is reducing the environmental impact of a product via conserving natural resources and decreasing the amount of harmful effects in the manufacturing process (Bajpai, 2014). Also, the energy needed to recycle many materials and components of a product is less than the energy required to produce it originally (Morris, 1996). In the paper industry, for example, every tonne of recycled fibre that displaces a tonne of virgin fibre will bring 27% of total energy consumption saving for a company (Bajpai, 2014). The energy consumption, fuel for manufacturing, directly affects pollution emissions. Thus, companies can reduce their pollution emission via energy conserved. Hence, we need to consider other parameters related to energy consumption and recycling activities as part of cash flows in the product development project. Thus the cost of disassembly, cost of shredding, revenue of used parts, revenue of recycled material, etc. and benefit of energy reduction from energy saving as effective parameters have to be considered in the estimation of profits.

In general, the effective parameters are formulated based on the recycling process, development process, production process, and energy consumption, in order to calculate the pollution emissions tax, as depicted in Figure 6.

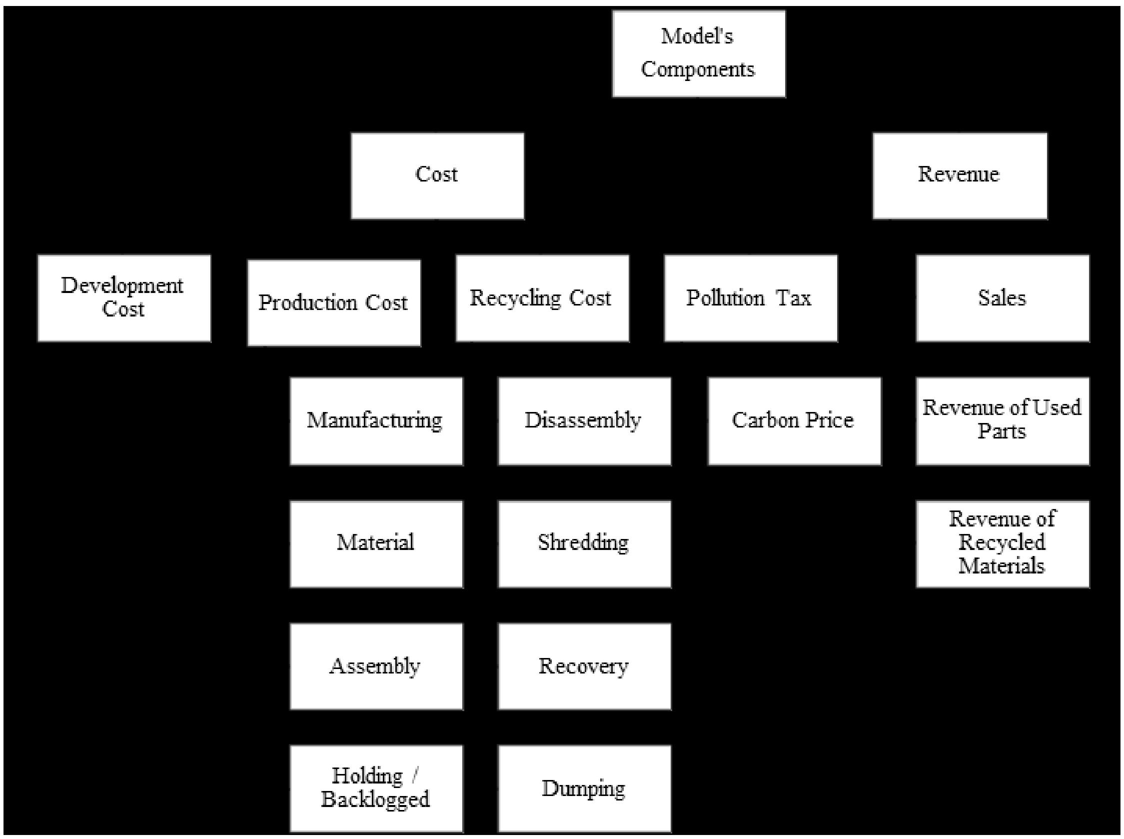


Figure 6 Cost and revenue parameters of green products proposed as components of the model

3.1 Model Assumptions

In order to develop the model, the following simplifying assumptions were made:

1. We assume all parameters of the model are deterministic;

2. We assume a given percent of sold products will be returned by consumers at the product's end of life. This percent can be estimated based on historical data of similar products on the market;

3. Different periods can be defined based on the type of product, such as: years, months, or even weeks;

4. When a product is designed for recycling purpose, it should be designed based on design for disassembly (DFD) methods for easy disassembly in the recycling process. So, we assumed components of the product are designed based on DFD to be disassembled easily.

5. The model is designed for demonstration purposes to show that a decision maker could indeed use the model to predict profits by inputting data related to the environment and recycling process. Thus, logistic costs (such as warehouse or collection center for recycling) are not considered in this model, although it can have a significant effect on profit in some industries. We therefore assume that all production, and therefore recycling operations, takes place locally, or that the costs of transportation to the required location, are negligible. Where the costs cannot be ignored, the decision-maker should subtract the total cost from the results obtained from this model to have a more accurate prediction of profits.

6. The unit selling prices are constant for the product.

3.2 Mathematical Model

We used following notation to formulate the model (Table 5).

Table 5 Indices, sets, etc. of mathematical model

Indices	
t	period
i	component / part
j	connection
k	material
z	machine
l	level of carbon tax
Sets	
T	set of periods
V	set of parts
V_1	set of shredded parts
V_2	set of recovered parts
M	set of machines
M_1	set of shredding machines
M_2	set of manufacturing machines
H	set of materials
H_1	set of recovered materials
Parameters	
P_{s_t}	price of product in market at period t
$P_{u_{it}}$	value of part i in period t
$P_{m_{kt}}$	value of type k of recycled material to produce one unit of product in period t
D_c	development cost
U_{it}	material cost of part i in period t
$C_{mfct_{it}}$	manufacturing cost of part i in period t
$C_{a_{ijt}}$	assembly cost of part i to part j in period t

C_{d_t}	disassembling cost of one unit of product in period *t*
$C_{sh_{it}}$	shredding cost of part *i* in period *t*
$\mathrm{R_{ik}}$	required material *k* to repair part *i*
$l_{r_{kt}}$	recovery cost of material *k* in period *t*
W_{r_k}	weight of type *k* material to be recovered in a product
d_{c_t}	disposal cost of one ton of solid waste in period *t*
$\mathrm{W_d}$	weight of dumped waste of one unit of product
T_l	carbon tax rate in level *l* ($/kilogram)
k_{ij}	requirement time of separating part *i* from connection *j*
ϑ_t	available working time in period *t*
e_i	CO_2 emission produced for producing one unit of part *i*
σ_i	required time for fabricating the component *i*
δ_{iz}	required time for manufacturing component *i* which should be made by machine *z*
$\emptyset_{ij}$	CO_2 emission produced for assembling part *i* to part *j*
O_{p_t}	fixed energy overhead of production in period *t*
O_{r_t}	fixed energy overhead of recycling in period *t*
F	CO_2 emission produced for recycling per unit of product
β_{ij}	required time to disconnect part *i* to part *j*
L_{a_t}	available time for assembling in period *t*
W_{iz}	weight of the part *i* which have to be shredded by machine *z*
φ_{zt}	capacity of machine *z* in period *t*
E_l	amount of CO_2 in level *l*
h_t	holding cost of one unit of product in period *t*
g_t	backorder cost of one unit of product in period *t*
d_t	customer demand in period *t*
R	large number
τ	product's life time
α	percent of sold products that will be returned by consumers at the product's end of life
Binary Variables	
η_l	$= 1$ if the carbon tax in level *l* is used, and $\eta_l = 0$ otherwise
μ_{1_t}	$= 1$ if at least one unit of product is produced in period *t*, and $\mu_1 = 0$ otherwise
μ_{2_t}	$= 1$ if at least one unit of product is recycled in period *t*, and $\mu_2 = 0$ otherwise

Integer Variables	
x_t	number of manufacturing products in period *t*
y_t	number of recycled products in period *t*
I_t	amount of inventory in period *t*
B_t	amount of backorder in period *t*
Continuous Variables	
${E_{production}}_t$	amount of emission that produced in manufacturing process in period *t*
${E_{recycling}}_t$	amount of emission that produced in recycling process in period *t*
E_{CO_2}	factory's total CO_2 emission

The following model total profit π through the product's life-cycle formulates our problem.

$$\max \pi = \sum_{t \in T} x_t P_{s_t} + \sum_{t \in T} y_{t+\tau} \left(\sum_{i=1}^{n} P_{u_{it}} + \sum_{k=1}^{v} P_{m_{jt}} \right)$$
$$- \left[D_c + \sum_{t \in T} x_t \left(\sum_{i=1}^{n} U_{it} + \sum_{i=1}^{n} C_{mfct_{it}} + \sum_{j=1}^{n} \sum_{i=1}^{m-g} C_{a_{ijt}} \right) + \sum_{t \in T} h_t I_t + \sum_{t \in T} g_t B_t \right.$$
$$+ \sum_{t \in T} y_{t+\tau} \left(C_{d_t} + \sum_{i \in V_1} C_{sh_{it}} + \sum_{i \in V_2} \sum_{k=1}^{m} R_{ikt} + \sum_{k \in H_1} l_{r_{kt}} W_{r_k} + \mathrm{d}_{\mathrm{c}_t} \times \mathrm{W_d} \right)$$
$$\left. + \sum_{l=1}^{n} T_l \eta_l E_{CO_2} \right]$$

Subject to:

$$y_{t+\tau} \le \alpha (d_t - B_t) \qquad t + \tau \in T \text{ and } \forall\, t \in T \qquad (1)$$
$$y_{t+\tau} = 0 \qquad t + \tau \notin T \text{ and } \forall\, t \in T \qquad (2)$$
$$\sum_{j=1}^{n} \sum_{i=1}^{m-g} k_{ij}\, y_{t+\tau} \le \vartheta_t \qquad \forall\, \tau \in T \qquad (3)$$

$$\sum_{i\in V_1} W_{iz}\, y_{t+\tau} \leq \varphi_{zt} \qquad \forall\, z \in M_1 \text{ and } \forall\, t \in T \qquad (4)$$

$$E_{CO_2} \leq \sum_{l=1}^{n} E_l\, \eta_l \qquad (5)$$

$$\sum_{l=1}^{n} \eta_l = 1 \qquad (6)$$

$$E_{CO_2} = \sum_{t\in T} (E_{production_t} + E_{recycling_t}) \qquad (7)$$

$$E_{production_t} = \sum_{i\in V_2} e_i (x_t - y_{t+\tau}) + \sum_{i\in V-V_2} e_i\, x_t + \sum_{j=1}^{n} \sum_{i=1}^{m-g} \emptyset_{ij}\, x_t + O_{p_t} \mu_{1_t} \qquad \forall\, t \in T \qquad (8)$$

$$x_t \leq R\mu_{1_t} \qquad \forall\, t \in T \qquad (9)$$

$$E_{recycing_t} = F y_{t+\tau} + O_{r_t} \mu_{2_t} \qquad \forall\, t \in T \qquad (10)$$

$$y_{t+\tau} \leq R\mu_{2_t} \qquad \forall\, t \in T \qquad (11)$$

$$\sum_{i=1}^{n} \delta_{iz}\, x_t \leq \varphi_{zt} \qquad \forall\, z \in M_2 \text{ and } \forall\, t \in T \qquad (12)$$

$$\sum_{i=1}^{n} \sigma_i\, x_t \leq \vartheta_t \qquad \forall\, t \in T \qquad (13)$$

$$\sum_{j=1}^{n} \sum_{i=1}^{m-g} \beta_{ij}\, x_t \leq L_{a_t} \qquad \forall\, t \in T \qquad (14)$$

$$x_t + I_{t-1} - B_{t-1} - d_t = I_t - B_t \qquad \forall\, t \in T \qquad (15)$$

$$\psi_l \leq R\eta_l \qquad \forall l \in L \qquad (16)$$

$$\psi_l \leq E_{CO_2} \qquad \forall l \in L \qquad (17)$$

$$\psi_l \geq E_{CO_2} - R(1 - \eta_l) \qquad \forall l \in L \qquad (18)$$

$$\eta_l \in \{0,1\} \qquad (19)$$

$$\mu_{1_t}, \mu_{2_t} \in \{0,1\} \qquad \forall\, t \in T \qquad (20)$$

$$E_{production_t}, E_{recycling_t} \geq 0 \qquad \forall\, t \in T \qquad (21)$$

$$E_{CO_2} \geq 0 \tag{22}$$

$$x_t, y_t, I_t, B_t \geq 0 \; integer \qquad \forall\, t \in T \tag{23}$$

3.3 Model Description

A product is made of a number of discrete parts, or components, and connections, which physically link the components (Lambert & Gupta, 2005). Some of these components and connections can be sent back to the operation process via recycling in the product life cycle. Product life cycle recycling can include material recycling, production waste recycling, reusing and remanufacturing, and or disposable product recycling. In general, the recycling process can be divided into four main steps, including disassembly of components, shredding of some components for material recycling, recovery of reusable components and connections, and disposal of the remaining components which are not usable in the manufacturing process, as depicted in Figure 7 (Chen, Navin-Chandra, & Prinz, 1994).

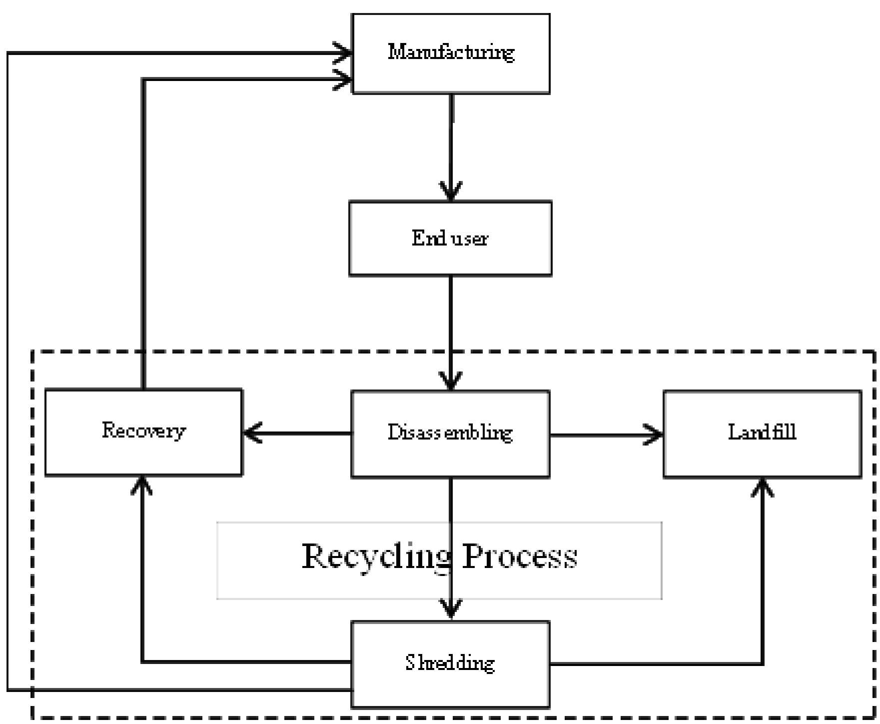


Figure 7 Recycling process of products in product life-cycle

The model's objective is to maximize the total profit of company through the product's life-cycle. The objective function is comprised of costs subtracted from revenues. Revenues include sales revenue and recycling revenue (revenue of used parts and recycled materials), while costs include product development cost, production cost (material cost, manufacturing cot, and assembly cost), holding cost, backlogged cost, recycling cost (disassembly cost, shredding cost, recovery cost, and disposal cost), and carbon price.

As per our assumption, only a given percent of sold products, Alpha (α), will be returned by consumers at the product's end of life. Although we assumed α can be estimate based on historical data of similar products on the market, the company needs to determine the minimum of alpha to assess the risk of its investment. Breakeven analysis is a tool to help decision-makers determine the point at which a company has no additional profit from NPD (Radomes Jr & Arango , 2015). To estimate this point, decision makers need to compare total environmental and operation costs of a new product with that of existing (old) product (Kiatkittipong , et al., 2008). In this paper, breakeven point helps decision-makers to find out the minimum number of products that have to be recycled.

Although the model does not calculate the breakeven point of recycling process, the point can be estimated based on analysis of the profit's sensitivity to Alpha, as shown in the numerical example. Thus, constraints (1) and (2) restrict number of recycling products in each period based on historical data of similar products on the market with respect to breakeven point of recycling process.

3.3.1 Recycling costs

Typically, a company needs to install a set of machines and assign a group of workers in order to separate the desired components and retrieval of usable components from accumulated products. Consequently, recycling of a product has a given cost for the company in each stage. So, the recycling cost comprises cost of disassembly, cost of shredding, cost of recovery, and cost of disposal. Also, the company will be faced by some limitations due to machines and labor work capacities which are typically captured by working time.

3.3.1.1 Cost of disassembly

Disassembly is a systematic method of removing desired parts from a product, without any damage to the parts (Giudice, et al., 2006). It consists of four main tasks, including getting access, moving, removing, and collecting components (Lambert & Gupta, 2005). These tasks are costed either through labor or automation.

The disassembly process is a time consuming process in which product parts will be separated by machines or labor. Total requirement time of separating part i from connection j can be defined through $\sum_{j=1}^{n}\sum_{i=1}^{m-g} k_{ij}$ where n represents the number of different type of connections and m is the number of same type of joints in products, and g represents number of joints that connect parts of the same material (Chen, et al., 1994). Constraint (3) restricts the number of products that can be disassembled according to available working time in period t (ϑ_t).

3.3.1.2 Cost of shredding

After disassembling the desired parts, some of these components cannot be repaired for reuse while their raw materials can be returned in the production process. These components could be shredded, breaking components at particle size into small pieces, via milling, grinding, etc. in order to increase the material's homogeneity (Lambert & Gupta, 2005). The cost of shredding has to be estimated for each part separately since different types of parts which need different shredding methods might exist.

Also, a limitation should be defined for the number of products according to the maximum capacity shredding machine z in period t (φ_{zt}) based on the weight of the part i which has to be shredded by machine z (W_{iz}), as shown in constraint (4).

3.3.1.3 Cost of recovery

Some parts are worked on at the end of a product's useful life. The use of the secondary materials reduces environmental impact (Lambert & Gupta, 2005). So companies try to return some reusable parts or materials to the production process via recovery. In general, the recovery process includes recycling of materials in the manufacturing process and reuse of parts in assembly process. After disassembly, both shredded materials and disassembled parts need to be repaired before being returned to the production process. However, the effective factor of accounting a component recovery cost is its suitability for recovery. It can be determined by companies based on durability and separability. Thus, after selection testing, proper parts and materials will be sent for a recovery process. The cost of recovery becomes expensive with increasing depth of recovery operation. Thus, it is important to determine the volume of recovery (Giudice, et al., 2006). Hence, the cost of recovery for materials in each period can be calculated via material recovery cost of type k material in period t ($l_{r_{kt}}$), k may be steel, plastics, etc. based on weight of type k material to be recovered in a product (W_{r_k}) (Chen, et al., 1994). Furthermore, recovery cost of parts can be calculated based on the sum of the cost of required materials to repair part i in period t ($\mathrm{R_{ikt}}$).

3.3.1.4 Cost of disposal

Once the suitable components and materials have been recovered, the useless parts of the product will be sent to waste disposal sites. The waste will be dumped via incineration or landfill. Incineration can bring energy recovery while it is reducing the waste volume (Lambert & Gupta, 2005). Many wastes have organic materials which can be burnt in an incinerator. So, the produced energy can be recovered via a boiler, for example, to generation electricity. Finally, the rest of the waste will be sent to landfill sites. In fact, landfill is the least attractive option in waste management (Williams, 2005). We assumed the same cost for incineration and landfill, to model the disposal cost of materials and components, based on the weight of dumped waste of the product (W_d). Disposal cost can thus be estimated via Equation (6) (Chen, et al., 1994).

3.3.2 Recycling Benefits

As mentioned before, some parts and materials of recycled products can be returned to the production process via recovery. Thus, two types of revenues can be defined based on recycling of reusable parts or the recycled materials (Chen, Navin-Chandra, & Prinz, 1994). Each type of revenue can be formulated according to following parameters.

3.3.2.1 Revenue of used parts

Some parts and modules of a product can be reused in the product's end-of-life as spare parts or in other items (Lambert & Gupta, 2005). All the usable parts will be recovered to be reused in new products. Thus, instead of each part which is used in the new products, companies acquire given revenues according to value of the part. Revenue of used parts for a product can be estimated based on total value of recovered parts that used in the product.

3.3.2.2 Revenue of recycled material

An important part of recycling is the recovery of materials out of scrap from end-of-life products (Lambert & Gupta, 2005). Recovered materials can be returned to the production process with other raw materials. That's why these are as valuable as recovered parts for companies. Hence, revenue of recycled materials can be estimated from total value of recovered materials in producing of a product.

3.3.3 Product Development Cost

New product development is a multi-stage process (Murthy, et al., 2008), whereby each stage of this process needs a given budget which is typically calculated based on the number of people that work as a project team, duration of the development project, and tools that are needed for production up to the design process (Ulrich & Eppinger, 2012). These costs are not related to the number of products. So the development costs are considered as fixed costs.

3.3.4 Carbon Price

A carbon price or carbon tax is the amount that must be paid as a tax or the permit cost in exchange to the equivalent CO_2 emission per tonne of greenhouse gases (British Columbia, 2014). Different kinds of energy are used in manufacturing and assembly processes. The amount of emitted carbon dioxide (CO_2) can be calculated based on the consumed energy. However, carbon tax of used energy is calculated based on policies and legislations in different areas. For example, in British Columbia (Canada) the carbon tax rates by fuels where natural gas used in stationary engines of factories has a price of 5.7¢ per cubic metre or about $1.5 per gigajoule (Tax Bulletin of British Columbia, 2013), while, in Australia the carbon tax is based on the total emitted carbon dioxide which was about 23$/tonne in 2012 (Australian Government, 2012).

In general, the total carbon tax of a factory varies with different countries' policies regarding the initial permits and excessively produced carbon dioxide. Carbon price rates in different countries are similar to the governmental tax which can be even piecewise, stepwise or a linear function depending on the carbon dioxide emission.

In this model, we assume a stepwise function in order to calculate the manufacturer's carbon tax, as shown in Figure 8. Thus the carbon tax is calculated based on the amount of factory's total CO_2 emission (E_{CO_2}) and the carbon tax rate in level l (T_l). Constraints (5) and (6), also, restrict the model to select proper carbon tax rate level based on the amount of CO_2.

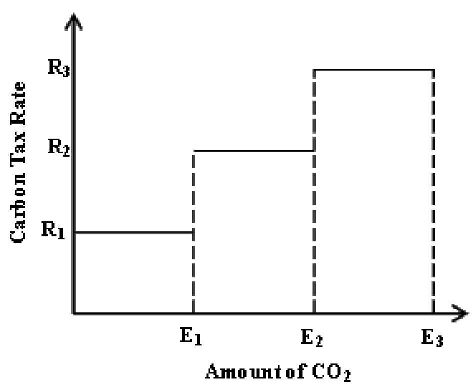


Figure 8 Stepwise function of Carbon Tax

On the other hand, energy use of a production system in typical plants can be divided into two parts including: 1) fixed energy overhead, and 2) marginal energy per unit of product (Pears, 2004) [Figure 9]. Therefore, the CO_2 produced by energy consumed for producing products can be estimated through the constraints (8) and (9). Moreover, the energy used for recycling products is producing a given CO_2 emission that is estimated by constraints (10) and (11).

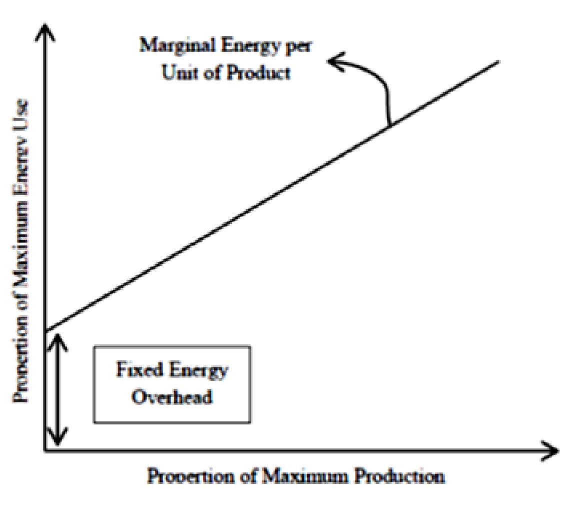


Figure 9 Energy use of a typical production system (Pears, 2004)

3.3.5 Production cost

When a product is designed based on recycling capability, production cost can be defined according to three main parameters; material cost, manufacturing cost, and assembly cost (Giudice, et al., 2006). Also, a company may have inventory or backorder according to customer demand, so holding and backlogged cost can occur based on a difference between the amount demanded and the amount of produced in each period.

3.3.5.1 Materials Cost

Material cost can be defined as the related cost of materials per unit of products in period *t*.

3.3.5.2 Manufacturing Cost

Two main parameters of manufacturing are labor and machine costs. Cost and limitation of production can be assessed based on these parameters.

In a production process different type of machines will be used to assemble or form the components of the product, so a set of machines (B) with a limited capacity (φ_{zt}) are considered in order to produce the component of products in period t. Constraint (12) limits the number of products produced according to capacity of the machines. Likewise, a company has a limited work force in a manufacturing process. This limitation can be captured by time. Constraint (13) restricts the number of products according to available working hours in period t (ϑ_t).

3.3.5.3 Assembly Cost

Assembly cost can be calculated based on total cost of connecting parts i and j together. The number of products can be limited in the assembly process according to constraint (14). Also, just as in the disassembly process, a given time (β_{ij}) is needed to connect between part i and j.

3.3.6 Holding Cost and Backlogged Cost

Holding cost and backlogged cost occur when a manufacturer will be faced with positive stock due to shortage of demand (inventory) or negative stock because of excess demand (backorder) in each period.

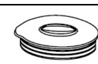
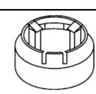
The number of products is restricted by demand in each period, as shown in constraint (15).

The final model is non-linear because η_l is a binary variable and E_{CO_2} is a continuous variable. It can be solved either by non-linear programming or by linear programming through constraints (16), (17), and (18), which are linearizing the model by defining $\psi_l = \eta_l E_{CO_2}$, where, ψ_l is a continuous variable ($\psi_l \geq 0$).

3.4 Numerical example

An electric juicer producer decides to develop a current model (A-0) of a blender which has about $2,300,000 annual profit. It should be noted again that the logistic costs are not considered in the annual profit of the company. The producer wants to introduce a new model (A-1) with recyclable capability which is designed based on new materials which are compatible with the environment and it can be disassembled easily. We assumed that the company is operating from its current, local facilities to collect products at the products' end of life with negligible cost for the transportation to the recycling process, so the same logistic costs can be considered for the current model (A-0) and the new model (A-1) of blender. The blender consists of seven parts, each of which needs a different type of process for recycling, as shown in Table 6.

Table 6 Recycling process of blender's components in the numerical example

Part ID	Part name	Shape	Shredding	Recovery	Dumping
P_1	Bowl		✓	✓	✓
P_2	Lid		✓	✓	✓
P_3	Adaptor			✓	
P_4	Blade Assy.		✓		
P_5	Coupler Assy.			✓	
P_6	Ring seal			✓	
P_7	Plain washer				✓

Before starting the test and prototype processes, managers need a proper forecast of the economic performance of this product in the future based on a trade-off analysis. They need useful information in this step (such as: number of products that have to be produced, number of recycled products and the amount of CO_2 emission based on produced and recycled products) in order to take a decision about the future of the project. Also, they expect a maximum of 40 percent of the total products sold in each period to be returned for recycling at the end of the product's life. Based on a given data (which is generated according to a realistic data from an electronic appliances manufacturer in Iran, as shown in appendix A), crucial information can be obtained via the model presented in order to help the managers make decisions.

This problem is solved using CPLEX (OPL 12.5.1.0 model), as shown in the Appendix B. The result shows (Table 7) that the company needs to produce and sell 20,769 units of the product seasonally while it will have 1231 units and 462 units of backordered demand in season one and season two respectively and 2307 units and 12,876 units inventory at season three and season four respectively according to the current demand of the product in each season in the market. Also, 23,322 units (23322=8307+7815+7200) should be collected for recycling in a year. Eventually, the company can achieve greater than $2,383,000 annual profits which is about 3.7% greater than of the company's current annual profit, from this product. However, if we do not consider the recycling stage of products (end of products' life-cycle), results show (Table 8) the company can achieved less than $2,252,000 annual profit which is about 2.1% less than of the company's current annual profit. Therefore, the managers can be assured that continuing the development project will not only decrease the environmental impact, but the company will also obtain increased profits, whereas the project has to be stopped based on the particular stage (i.e. production stage) analysis. Also, the results show some useful information. For instance, the total

CO_2 is 37, 386 kilograms, which means that the maximum carbon tax rate ($0.32 per kilogram) should be paid by the company.

Table 7 Results of numerical example based on all stages of the product life-cycle

Period	Number of manufacturing products	Number of recycled products	Amount of inventory	Amount of backorder	Amount of emission that produced in manufacturing process	Amount of emission that produced in recycling process
t	x_t	y_t	I_t	B_t	$E_{production}$	$E_{recycling}$
1	20769	0	0	1231	7626.8	0
2	20769	8307	0	462	7032.9	3040.5
3	20769	7815	2307	0	7068.1	2863.4
4	20769	7200	12876	0	7112	2642

Table 8 Results of numerical example based on production stage of the product life-cycle

Period	Number of manufacturing products	Number of recycled products	Amount of inventory	Amount of backorder	Amount of emission that produced in manufacturing process	Amount of emission that produced in recycling process
t	x_t	y_t	I_t	B_t	$E_{production}$	$E_{recycling}$
1	20769	0	0	1231	7626.8	0
2	20769	0	0	462	7626.8	0
3	20769	0	2307	0	7626.8	0
4	20769	0	12876	0	7626.8	0

As mentioned, the breakeven point of the number of products that have to be recycled is an effective factor in a managers' decision regarding the recycling process. In this example, the breakeven point of Alpha, the percent of sold products that have to be returned for the recycling process, is about 0.15, as illustrated in Figure 10. This means that at least 15 percent of the total products that are sold by the company have to be returned for the recycling process. Also, two scenarios are defined in order to analyse the total profit's sensitivity to Alpha. Scenario one: the profit is analysed based on the recycling of the optimal number of returned products in a different value of Alpha. Scenario two: the profit is analysed based on the recycling of the maximum number of returned products in different values of Alpha.

The results show, in Section A, that the total profits of both scenarios are less than current situation, so at this level, the project has to be stopped. In Section B, not only do both scenarios have approximately the same profit in each point, but also the profits are greater than the current profit of company. In Section C, however, each scenario exhibits different behaviors. The profit of the company will be maximized and constant when the optimal number of returned products is recycled, while the profit of the company will be decreased when the maximum number of returned products is recycled. Even after point D, the profit will be less than the current profit of the company.

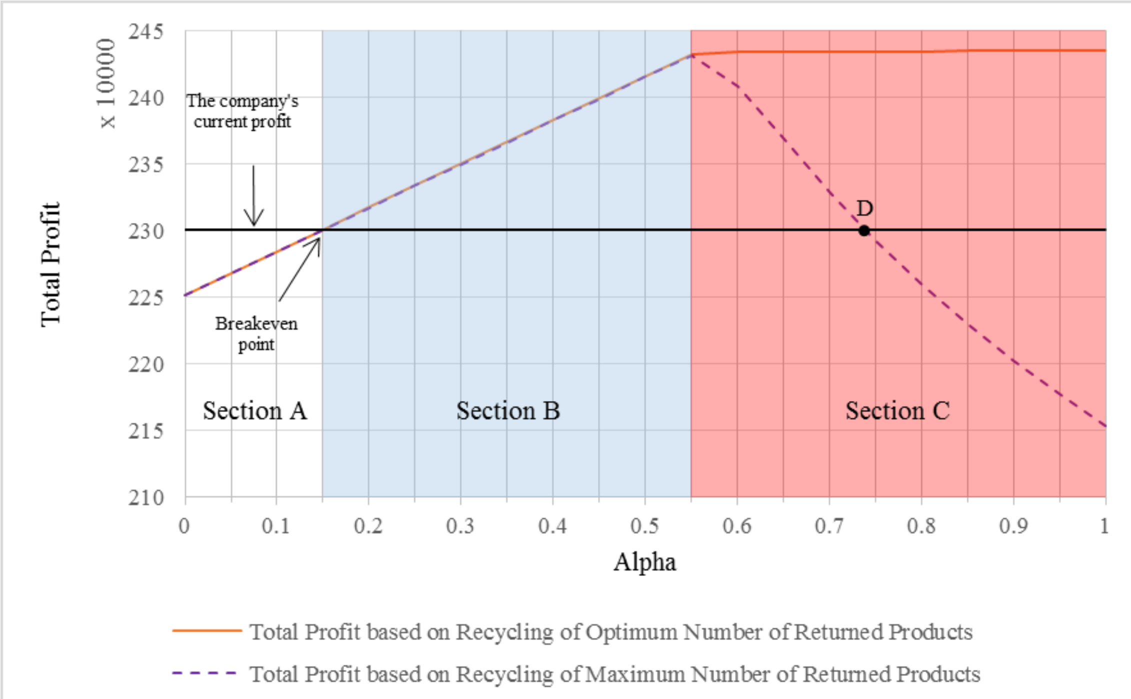


Figure 10 breakeven point and sensitive analysis of profit to the Alpha

In general, the model gives a forecast of the amount of products that should be produced and the amount of products that should be recycled in each period to reach the maximum profit over the expected time period. In this example, the expected time is one year that is divided into four periods, which represents the seasons of the year. Also, it shows the amount of CO_2 which is produced in each period based on the amount of produced and recycled products in order to calculate the carbon tax. In this example, a stepwise function is defined for calculating the tax. This information gives managers have a view of the economic effect of the project in the future. Nevertheless, it has some limitations, such as: it cannot calculate the net profit of the recycling process separately. Also, logistic costs (such as warehouse or collection center for recycling) are not considered in this model, although it can have a significant effect on profit in some industries such as electronic appliances manufacturer.

4. A Dynamic model for Profit Analysis of New Green Product Development in the Automotive Industry

In Chapter 3, a general framework was introduced by a mixed-integer model for profit analysis of sustainable products based on the life-cycle thinking, while we considered deterministic demand for the model. However, in reality, the product demand is subject to uncertainties (i.e., stochastic). In this chapter of the thesis, the primary model is further developed based on a stochastic demand and the best policy, which represents the level of greenness for a product in each period of time, to reach maximum profit. Thus, a dynamic model is proposed, based on dynamic programming and qualitative choice models, to support decision makers to analyze the profit of a set of products, which are designed based on DFE strategies. The model considers the effect of different parameters, such as: sensitivity to environment and salary of a consumer, maintenance and operating cost, and price of a product, etc., on the product's demand in order to recognize the characteristics of potential consumers to achieve optimum demand. Also, the model helps decision makers to control the mid-term and long-term strategies of each NPD project through budget allocation.

4.1 Model's Assumptions

A dynamic model is proposed to analyze the profit of a company that decides to develop a set of its current automobiles based on DFE strategies.

The problem is formulated based on the following assumptions:

1. As mentioned, in 2009 Government of Canada with the Design Exchange (DX) and Canadian Manufacturers and Exporters (CME) assessed North American's industries' practices in DFE

based on three main strategies. The result of this survey shows that more than 40% of North American companies in the automotive industry that applied DFE, design their products for energy and emission efficiency, about 40% of them design green products based on recyclability and environmentally friendly disposal strategy, while less than 20% of companies design for reduced packaging (Industry Canada, 2009). Thus, in this model, the product's life cycle, as illustrated in Figure 11, is defined based on energy and emission efficiency and recyclability and environmentally friendly disposal strategies, which are applied by automotive manufacturers in North America.

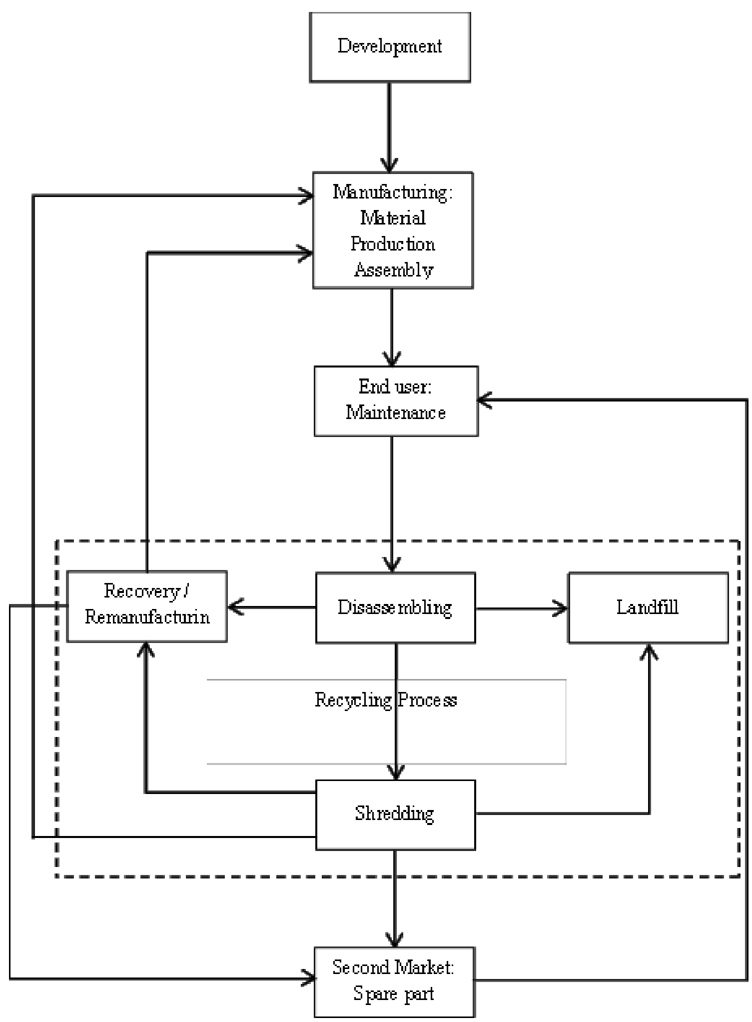


Figure 11 Life-cycle process of a green product designed based on recyclability strategy

2. The model is designed based on a product family-based approach, since automotive companies like many firms in other industries prefer to develop a family of products in order to tackle intense competition and rapid technological advances, and to decrease the development cost and risk (Loch & Kavadias, 2008; Jiao, Simpson, & Siddique, 2007). A product family-based approach helps to decrease fixed costs of design and procurement of a product's components through the idea of platform-based design (Gupta & Krishnan, 1999). In the automotive industry, for instance, a platform can be designed based on recyclability and an environmentally friendly disposal strategy and use it for different types of cars. Likewise, an engine can be designed based on energy and emission efficiency strategy for use in different hybrid cars. Thus the model is defined based on a set of vehicles that can be developed as a product family denoted V.

3. The level of environmental performance of a product can be introduced based on environmentally friendly materials, recycled content, recyclability, clean energy, emissions, and returnable and recyclable packaging (Ulrich & Eppinger, 2012). Thus, we assumed a sub-class of vehicles can be introduced to the market in different levels of environmental performance in each period. For example, the class one of car type A (Model A1) can be introduced to the market in year one if 25% of the total components of car is developed based on DFE strategies. Also, the class A2 will be presented when the company designed the 50% of total components of the car based on DFE strategies and so forth. Therefore, the last class represents the entirely environmental friendly car that all the components are designed based on DFE strategies.

4. No production capacity is assumed for the model, so unlimited vehicles can be produced and recycled in each time period.

4.2 Dynamic Model

Product development is a time consuming process in which the number of people and duration of the project contribute to estimating the cost of this process (Ulrich & Eppinger, 2012). So the decision of management regarding the duration of each project in the product family has a significant effect on the total profit of company. A dynamic model provides a general framework for analyzing the effect of different policies on a company's profit in multiple-period consequences (carry-over benefits) of the NPD investment. It helps management to organize the development process of each project (vehicle) in each period based on different parameters. A dynamic model is composed of stage, state variables, decision variables, transition function, and an objective function (Powell, 2011).

We used following notation to formulate the model

Indices	
t	period
i	product / car in the product family
z	product / car of rivals
j	level of greenness
j'	level of greenness in previous periods
t'	previous periods of t
q	consumer
Sets	
T	set of periods
L	set of level of greenness in each vehicle
J	set of modules of a car
B_ς	set of product family

B_η	set of rivals' products
Parameters	
b_t	available R&D budget in period *t*
l_{it}	level of greenness for vehicle *i* in period *t*
$o_{ijj'}$	operational cost of developing vehicle i from level j' to j
α_t	a percent of total profit in period *t* that have to be added to the next period of development budget
π_t	total profit of company in period *t* (payoff from initial choice in period *t*)
$V_{qi,t+1}$	utility function of consumer q from vehicle *i* in period *t+1*
Y_{t+1}	consumer's income in period *t+1*
$r_{il_{it}}$	price of vehicle *i* in level l_{it}
$c_{il_{it}}^{opra}$	average operating cost of vehicle *i* in level l_{it}
$e_{qil_{it}}$	degree of sensitivity to environment in consumer q from vehicle *i* in level l_{it}
ε	vector of both consumers and vehicles other observed and unobserved variables that affect the consumer q's utility of vehicle *i* (e.g. age, education, seats, luggage space, etc.)
p_{it}	probability of product *i* in period *t*
λ_ς	measure of correlation of unobserved variables within subset B_ς
λ_η	measure of correlation of unobserved variables within subset B_η
x_{it}	number of individuals that selecting vehicle *i* in period *t*
γ	discount factor
β	percent of sold products that will be returned by consumers at the product's end of life
$c_{il_{i,t-1}}^{pro}$	production and logistic cost of one unit of vehicle *i* in level $l_{i,t-1}$
$c_{il_{i,t-1}}^{ser}$	warranty cost of one unit of vehicle *i* in level $l_{i,t-1}$
$C_{il_{i,t-1}}^{CO_2}$	carbon tax of producing one unit of vehicle *i* in level $l_{i,t-1}$
$r_{il_{i,t-\tau}}^{recy}$	total revenue that can be obtained from recycling of vehicle *i* in level $l_{i,t-\tau}$
$c_{il_{i,t-\tau}}^{recy}$	total cost from recycling of vehicle *i* in level $l_{i,t-\tau}$
τ	product's life time
Binary Variables	

a_{ijt}	= 1 if j level are completed for vehicle i in period t, and a_{ijt}= 0 otherwise

4.2.1 Stage:

The company division for new budget allocation decision is based on constant time intervals (e.g. every year). So, the stages of the model are defined according to different time periods. In dynamic programming, each stage represents a new small problem to be solved in order to plan for the next closest time (Chinneck, 2012).

4.2.2 State Variable:

A state comprises a set of variables that determine the set of feasible policies in each stage (Powell, 2011).

Let the set of components in the vehicle i be divided into J subsets, where J represents a main module of a car (e. g. body, engine, electronic, wheels, etc.). Thus, the level of greenness can be defined based on the number of modules that designed according to DFE strategies. Also, let the set of vehicles be partitioned into N subsets, where each subset comprises j classes, denoted B_i. So, the states of class are designed based on two variables.

1. L_t is the set of level of greenness in each vehicle in period t

   $L_t = \{l_{1t}, l_{2t,}, \dots, l_{Nt}\}$; l_{it}= level of greenness for vehicle i in period t

2. b_t is available R&D budget in period t

4.2.3 Decision Variable:

We assumed the R&D is given for each class of vehicle i, so, following decision variable can be defined for the model.

- a_{ijt}= 1 if j level are completed for vehicle i in period t, and a_{ijt}= 0 otherwise

4.2.4 Transition function:

The transition function explains the relation between the next state of the process and the current state of the process and the current decision taken (Bradley, et al., 1977). So, the transition of number of completed levels for vehicle i in period $t+1$ can formulate based on Equation (24).

$$l_{i,t+1} = \max\{jI_{a_{ijt}}, l_{it}\} \qquad (24)$$

Equation (25) restricts the model to make infeasible solution.

$$a_{ij't'} \leq 1 - a_{ijt} \qquad j' < j \quad and \quad t' < t \qquad \forall\ i = \{1, \dots, N\} \qquad (25)$$

We assumed, a given percent of total profit of company will be added to the development budget in the next stage, while the development budget in first period ($t=0$) is given. Thus, the transition function of available development budget in time $t+1$ can be described based on Equations (26).

$$b_{t+1} = b_t - \sum_{i=1}^{N} \sum_{j=l_{it}+1}^{L} o_{ijj'}\, a_{ijt} + \alpha_t \pi_t \qquad j' = l_{it} \qquad (26)$$

We have limited development budget in time t that have to be allocated to each project. In order to avoided infeasible decisions, budget is restricted at period t, as shown in Equation (27):

$$\pi_{t+1}(S') = \begin{cases} -\infty & if \;\; S' < 0 \\ \pi_{t+1} & if \;\; S' \geq 0 \end{cases} \qquad\qquad S' = b_{t+1} - \alpha_t \pi_t \tag{27}$$

As depicted in Figure 12, demand of a new product is different in the product's life-cycle by splitting the maturity stage of the product in markets (Pride, Hughes, & Kapoor, 2012; Griffin, 2012).

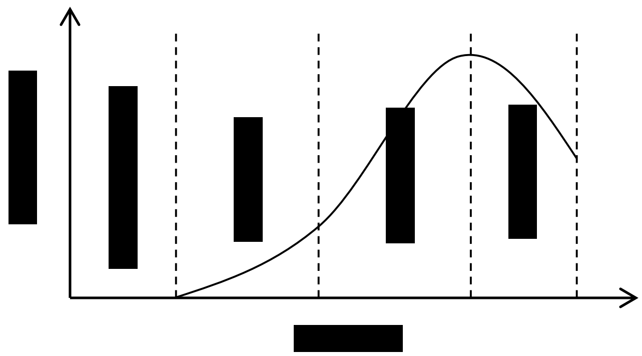


Figure 12 a new product's demand based on its maturity in the market

A purchase is conducted when the consumer receives higher happiness or utility from the product than the rival's existing products. The marginal utility is made from a bundle of the product's attributes which consumers received (Loch & Kavadias, 2008). Numerous studies have addressed many parameters effect on marginal utilities which received by consumers (Train, 1993; Straughan & Roberts, 1999; Young, et al., 2010; Dagher & Itani, 2014). In the automotive industry, however, purchasing cost, operating cost (e.g. fuel cost, maintenance cost) and some measure of size (e.g. weight, luggage space, seats, and horsepower) are main characteristics of a vehicle that affect consumer's demand (Train, 1993). At the same time, some constraints such as: lack of time for research, high prices, lack of information, and income will effect on consumers' behavior to purchase of green products (Young, et al., 2010; Brécard, et al., 2009) Also, degree of sensitivity to impact of a product on environment can be seen by consumers as a specific feature (Brécard, et al., 2009). According to these parameters, the indirect utility function of vehicle *i* for consumer q in time *t+1* can be defined by Equation (28)

$$V_{qi,t+1} = f\left(Y_{t+1}, r_{il_{it}}, c_{il_{it}}^{opra}, e_{qil_{it}}, \varepsilon\right) \tag{28}$$

Eventually, for estimating the probability of demand in each stage we used a disaggregate model, where the emphasis is on individual decision making, instead of aggregate models, which describe markets as a whole, for demand of green products based on Generalized Extreme Value (GEV) models. The GEV are qualitative choice models that calculate the probability that a consumer selects a specific alternative from a set of alternatives based on the correlation between unobserved parameters in each alternative. It means the probability of each alternative would increase when another alternative in the same subset is removed. (Train, 1993). A nested logit model is appropriate model of GEV models for this problem, because based on this model the available vehicles in markets can be clustered into *K* subsets, for any vehicle *i* and *z* in different subset that is *i* in B_ς and *z* in B_η, where $\varsigma \neq \eta$, the choice probability of vehicle *i* by consumer *q* in time *t* be calculated based on Equation (29) (Train, 2009).

$$p_{it} = \frac{e^{V_{it}/\lambda_\varsigma}\left(\sum_{z\in B_\varsigma} e^{V_{zt}/\lambda_\varsigma}\right)^{\lambda_\varsigma - 1}}{\sum_{\eta=1}^{N}\left(\sum_{z\in B_\eta} e^{V_{zt}/\lambda_\eta}\right)^{\lambda_\eta}} \tag{29}$$

Therefore, the transition function of demand for vehicle i in time *t+1*, the probably (Pr) of d_{it+1}, in a potential market of size *n* can be calculated by binomial distribution at period *t+1*, as shown in Equation (30).

$$\Pr(d_{it+1}|V_{it+1}, l_{it}) = \Pr(d_{it+1}: x_{it+1}) = \binom{n_{t+1}}{x_{it+1}} p^{x_{it+1}} (1-p)^{n_{t+1}-x_{it+1}} \quad (30)$$

Also, the binomial distribution approximates the normal distribution when *n* is large enough. Thus, the probability of d_{it+1} in a potential market of size *n* is calculating based on normal distribution function.

On the other hand, when a product is designed for recyclability and environmentally friendly disposal, it is returned for recycling process at a given time τ (the end of product life cycle), as illustrated in Figure 11. Thus, the number of returns in period $t+\tau$ has to be a function of the product demand in period *t*, as shown in Equations (31), and (32).

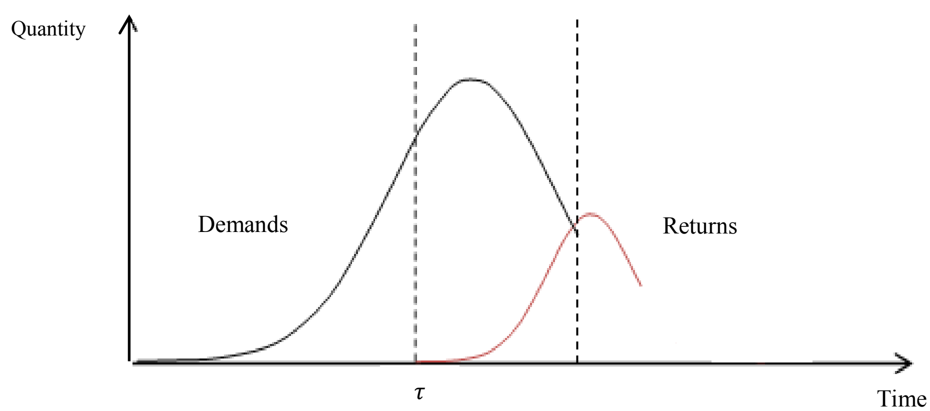


Figure 13 Return function

$$d'_{it} = \beta d_{it-\tau} \quad (31)$$

$$d'_{it} = \begin{cases} 0 & if \ \ t < \tau \\ \beta d_{it-\tau} & if \ \ t \geq \tau \end{cases} \quad (32)$$

4.2.5 Objective function

The model's objective is maximizing the total profit of the company in the process of development while it proposes the best policy in each period. We formulated this problem based on Bellman's model, since it is proposed a dynamic framework for budget allocation in NPD process while it is considered the present value of investments in the next periods (future cash flow), as shown in Equation (33).

$$g_t(L_t, b_t) = \max_{a_{ijt}}\{\pi_t(L_t, b_t) + \gamma E g_{t+1}(L_{t+1}, b_{t+1})\} \tag{33}$$

The total profit of company is designed based on Cost-Volume-Profit (CVP) analysis. Because the behavior of total revenue and total cost is linear, the product selling price, variable costs, and fixed costs are known, and also, change in profit arise only because of the demand of product (Horngren, et al., 2002). Also, the product costs can be divided into two parts; initial costs (development and production) and subsequent costs (maintenance, and recycling) during its life cycle (Niemann, et al., 2009). So, the total profit (π_t) of the company from the product family in period *t+1* is described based on Equation (34).

$$\begin{aligned}\pi_t = -\sum_{i=1}^{N}\left(\sum_{j=l_{it}}^{L} o_{ij,l_{i,t-1}}\, a_{ijt}\right) + \sum_{i=1}^{N}\left(r_{il_{i,t-1}} - c_{il_{i,t-1}}^{pro} - c_{il_{i,t-1}}^{ser} - C_{il_{i,t-1}}^{CO_2}\right) E[d_{it}] \\ + \sum_{i=1}^{N}\left(r_{il_{i,t-\tau}}^{recy} - c_{il_{i,t-\tau}}^{recy}\right) E[d'_{it}]\end{aligned} \tag{34}$$

4.3 Numerical example

An automotive company decides to develop the X-Series of a compact car based on recyclability and environmental friendly disposal strategy, and energy and emission efficiency strategy. The company's initial budget to develop this product family, includes three different compact cars, is $220,000,000. The company's policy is to assign 15% of total profit of these vehicles' sale to the next year's development budget. Also, they expect to introduce full green class of these cars in four years to the market. Thus, in order to keep the products' current market share, different sub-classes of each vehicle with different level of environment performance, will be introduced to the market in the first of each year.

Each car's components can be divided into three main modules, as shown in table 9. Also, four level of greenness are defined for each car, as shown in table 10.

Table 9 Three main modules of a car at the numerical example

Number	Module	Parts
1	Body & Interior	Doors, Windows, Car seats, Floor components and parts, Bearings, Hoses, Trap and Other miscellaneous parts
2	Electrical & electronics	Audio/video devices, Charging system, Electrical supply system, Gauges and meters, Ignition system, Lighting and signaling system, Sensors, Starting system, Switches, Wiring harnesses, Miscellaneous, and Air conditioning system (A/C)
3	Engine & Chassis	Braking system, Engine components and parts, Engine cooling system, Engine oil system, Exhaust system, Fuel supply system, Suspension and steering systems, and Transmission system

Table 10 Each car's sub-class based on level of greenness at the numerical example

Class	Level of Greenness	Modules that are developed based on DFE strategies
1	0%	-
2	33%	Body & Interior
3	66%	Body & Interior and Electrical & electronics
4	100%	Body & Interior, Electrical & electronics, and Engine & Chassis

If we assume just one vehicle, as a rival, is in the market. So the example is applied for four cars, three green cars and one non-green car, as illustrated in Figure 14.

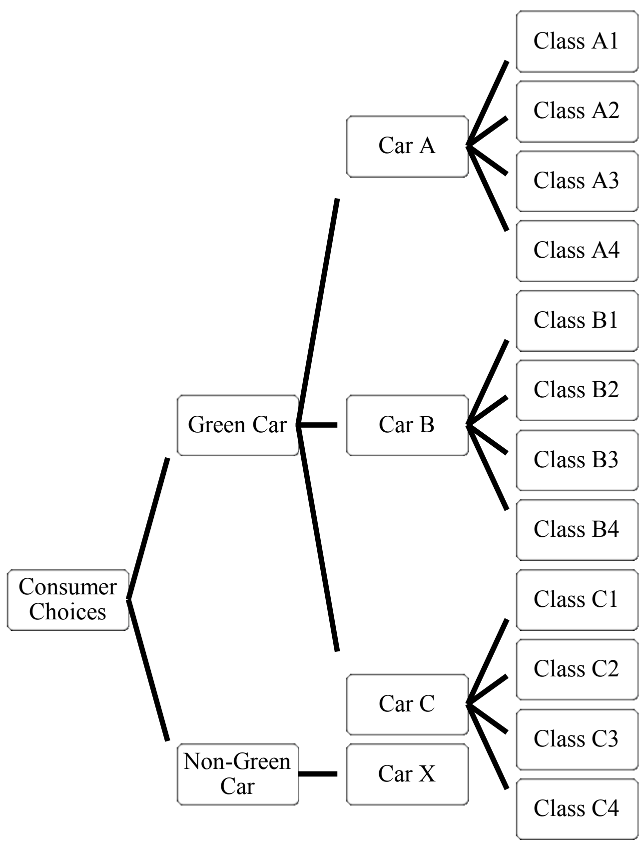


Figure 14 Number of cars in the numerical example

By dividing the available vehicles in the market into two sets, including the company's product family (B_1) with three vehicles and other vehicles in market (B_2) with *M* vehicles, the choice probability of vehicle *i* in time *t* be calculated based on following Equation.

$$p_{it} = \frac{e^{V_{it}/\lambda_1}\left(\sum_{z\in B_1} e^{V_{zt}/\lambda_1}\right)^{\lambda_1-1}}{\left(\sum_{z\in B_1} e^{V_{zt}/\lambda_1}\right)^{\lambda_1} + \left(\sum_{z\in B_2} e^{V_{zt}/\lambda_2}\right)^{\lambda_2}}$$

Therefore, based on a given data, as shown in Appendix C, the profitability of each new green car can be estimated based on the best policy used by managers in each period.

As shown in Figure 15, the model is a finite horizon dynamic program ($t = 4$) that if it is applied for two cars ($i = 2$) with three levels of greenness ($j = 3$), we will have nine states (j^i) and five stages ($t + 1$). Thus, 165 different paths ($\sum_{x=1}^{n=j^i}[x(n + 1 - x)]$) can be find for solving the problem. Also, if it is applied for the example, three cars with four level of greenness, we will have 64 states and five stages that made 45,760 different possible solutions. Therefore, we are facing with curse of dimensionality in this problem, so the model has to be solved based on backward induction algorithm (Powell, 2011).

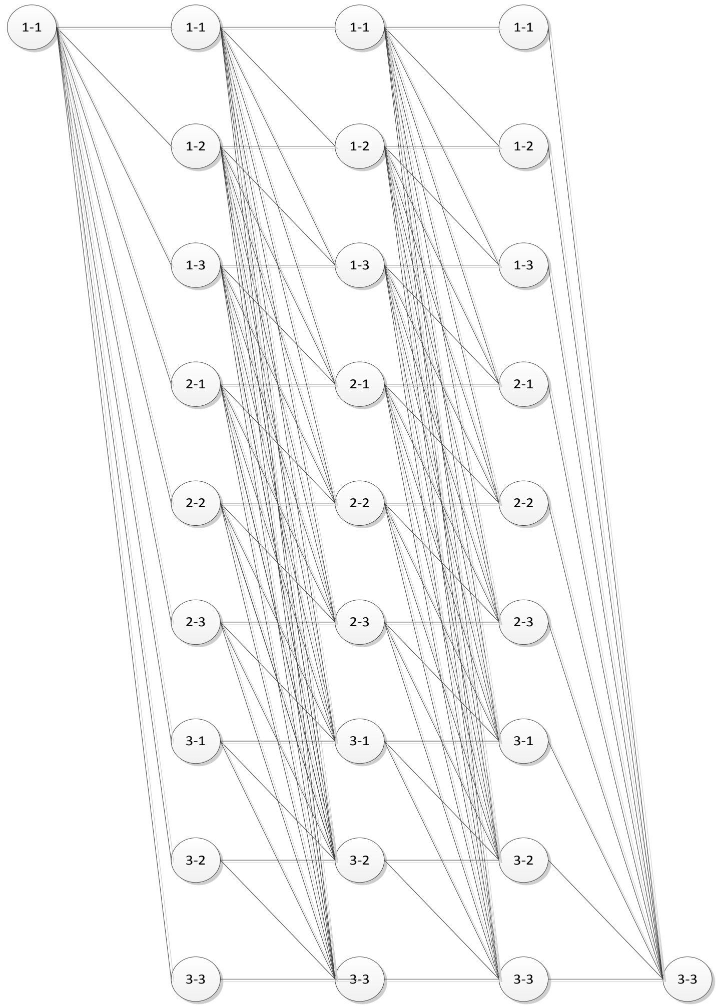


Figure 15 Potential solutions to develop two cars with three level of greenness. First number of each node represents the level of greenness of first product and second number represents the level of greenness of second product.

The result shows (Table 11) that the company can achieve $707,534,008 total profit in five years from the product family, whereas it loses $44,086,746 at the first year of introducing this product family to the market. At the same time, the company can expect to have 1,776,706 units of demand for different classes of this product family.

Table 11 Maximum profit and total demand of the company from the product family

Product	Total Demand	Total Product Family's Profit in Five Years with 1% Inflation
A	636,395	$707,534,008
B	612,878	
C	527,433	
Product Family's Total Demand	1,776,706	

The Product Family's Annual Profit				
Year 1	Year 2	Year 3	Year 4	Year 5
-$44,086,746	$219,190,693	$191,288,515	$154,190,832	$186,950,715

The result can be interpreted for each product as following:

1. As illustrated in the Table 12, the class two of car A has to be introduced to the market in first and second years, where the company can expect to sell about 242,671 (=121,297+121,374) units of this class. Also, 48,534 (=24,259+24,275) units of the car class A2 should be collected for recycling in upcoming years. In the third year, the full green class of car A has to be produced and introduced to the market. In the last two years, the company expects to increase its products sales to 265,608 (=134,251+131,357) units of this product, while 53,121 (=26,850+26,271) units of sold products have to be collected for recycling.

Table 12 Result of development of product A in each year

	Year 0	Year 1	Year 2	Year 3	Year 4
Level of Greenness	1	2	2	4	4
Demand	128,117	121,297	121,374	134,251	131,357
Choice Probability	-	0.243	0.243	0.269	0.263
Returns for Recycling	0	24,259	24,275	26,850	26,271

2. As illustrated in the Table 13, the class three of car B has to be developed in the first year. It is expected that 247,288 (=123,605+123,683) units of this class will be sold in first and second years, while 49,458 (=24,721+24,737) units of this class should be collected for recycling in upcoming years. In the third year, the full green class of car B has to be produced and introduced to the market. In third and fourth years, the company expect to sell 245,976 (=124,328+121,648) units of the full green class of car B and 49,196 (=24,866+24,330) units should be collected for recycling in upcoming years.

Table 13 Result of development of product B in each year

	Year 0	Year 1	Year 2	Year 3	Year 4
Level of Greenness	1	3	3	4	4
Demand	119,614	123,605	123,683	124,328	121,648
Choice Probability	-	0.247	0.247	0.249	0.243
Returns for Recycling	0	24,721	24,737	24,866	24,330

3. As illustrated in the Table 14, by contrast to other cars, the company has to develop the full green class of the car B in the last year, whereas the class three of the car has to be introduced to the market in first three years. The result shows the company will have at least 100,407 units of demand for the car class three in each of the first three years. Also, they can be expected to sell 107,827 units of full green class of this car in fourth year, while 21,565 units of them should be collected for recycling in upcoming years.

Table 14 Result of development of product C in each year

	Year 0	Year 1	Year 2	Year 3	Year 4
Level of Greenness	1	3	3	3	4
Demand	102,978	108,076	108,144	100,407	107,827
Choice Probability	-	0.216	0.216	0.201	0.216
Returns for Recycling	0	21,615	21,629	20,081	21,565

Sensitivity analysis is a what-if technique that helps to evaluate the behavior of the model when the original data or an underlying assumption is changed (Horngren, et al., 2002). Thus, for evaluating the behavior of this model different values are defined in order to analyse the total profit's sensitivity of each car to the correlation of unobserved variables in the product family's nest (λ_1) and initial investment on development process (initial development budget in time zero, b_0).

Different values are defined in order to analyse the demand of each product and the total profit's sensitivity to the correlation of unobserved variables in the product family nest (λ_1), as shown in Table 15. The result shows the total demand of each product has different behaviour by decreasing the correlation of unobserved variables in the product family nest, as illustrated in Figure 16. At the same time, the total profit of the product family will be increased by decreasing the correlation of unobserved variables in the product family nest, as illustrated in Figure 17. The result shows that the total profit is strongly correlated ($R^2 \cong 0.99$) to the correlation of unobserved variables in the nested logit model. When a problem is designed based on a non-linear equation in a model, This results in a linear solution for a parameter. On the other hand, if a model is linear, a non-linear result cannot be obtained. In this problem, the result of the sensitivity analysis shows that the total profit trend is close to linear by changing the value of the correlation of unobserved variables in the Nested Logit model, while the trend of each product's demand is non-linear.

Table 15 Sensitivity analysis of demand and profit to the $\boldsymbol{\lambda_1}$

$\boldsymbol{\lambda_1}$	**Demand of Product A**	**Demand of Product B**	**Demand of Product C**	**Profit ($)**
0.1	693,235	550,686	228,140	$518,665,679
0.2	623,456	555,746	355,411	$556,475,461
0.3	611,268	566,450	419,951	$595,854,979
0.4	614,763	580,797	463,846	$634,361,043
0.5	624,273	596,620	498,309	$671,656,656
0.6	636,395	612,878	527,433	$707,534,008
0.7	649,615	629,028	553,038	$741,847,434
0.8	663,154	644,761	576,047	$774,493,581
0.9	676,572	659,890	596,979	$805,403,330
1	689,605	674,303	616,151	$834,537,157

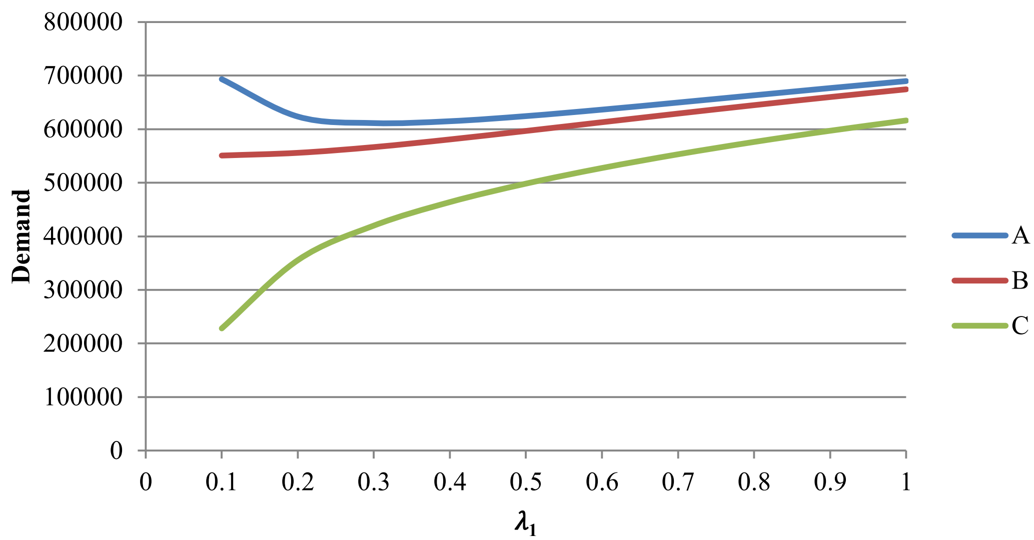


Figure 16 Sensitivity analysis of demand to the $\boldsymbol{\lambda_1}$

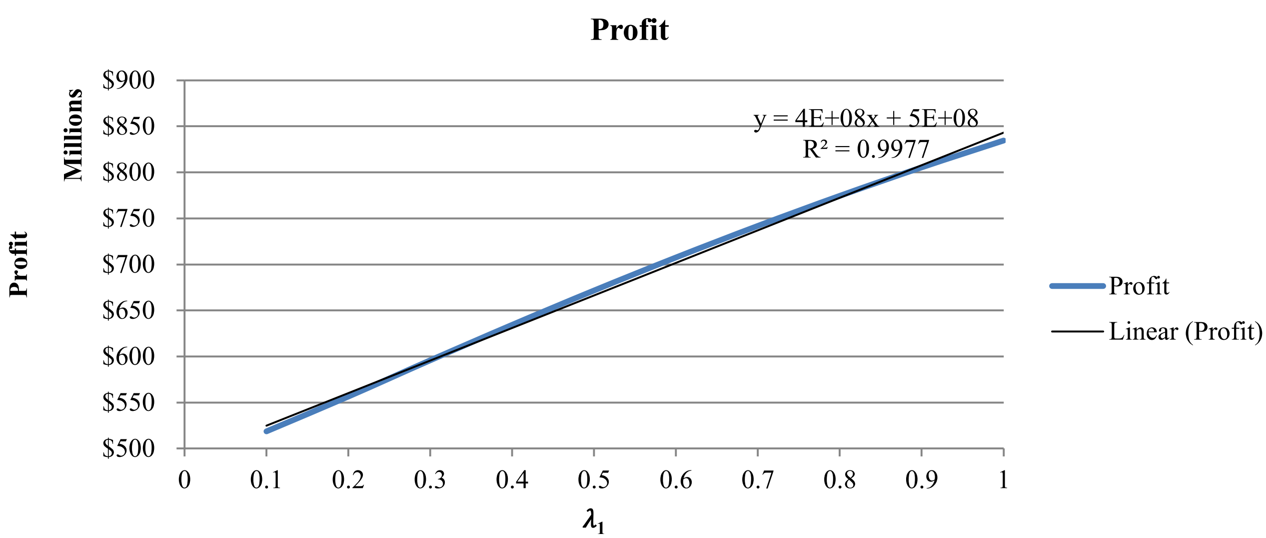


Figure 17 Sensitivity analysis of profit to the $\boldsymbol{\lambda_1}$

Also, the sensitivity of each product's demand and the company's total profit form the product family to initial budget, which is considered for development of the product family, are estimated by applying different initial development budget (b_0) values, as shown in Table 16. The result shows (Figure 18), the trend of the demand of product A is inversely proportional to the increase in initial budget, whereas the trend of the demand of product C is proportional. The trend of the demand of product B, however, is irregular to the increase the initial development budget value. In addition, sensitivity analysis of profit to the initial development budget shows the trend of total profit is proportional to the increase in initial budget.

Table 16 Sensitivity analysis of demand and profit to the initial development budget

Initial Budget ($)	Demand of Product A	Demand of Product B	Demand of Product C	Profit ($)
150,000,000	660,333	585,341	517,185	$565,824,296
160,000,000	660,333	585,341	517,185	$575,824,296
170,000,000	660,333	585,341	517,185	$585,824,296
180,000,000	644,857	621,236	505,598	$656,309,274
190,000,000	644,857	621,236	505,598	$666,309,274
200,000,000	629,756	615,654	529,674	$687,534,008
210,000,000	629,756	615,654	529,674	$697,534,008
220,000,000	636,395	612,878	527,433	$707,534,008
230,000,000	621,043	606,842	552,533	$720,977,893
240,000,000	627,603	604,195	550,188	$730,977,893
250,000,000	627,603	604,195	550,188	$740,977,893

Figure 18 Sensitivity analysis of demand to the initial development budget

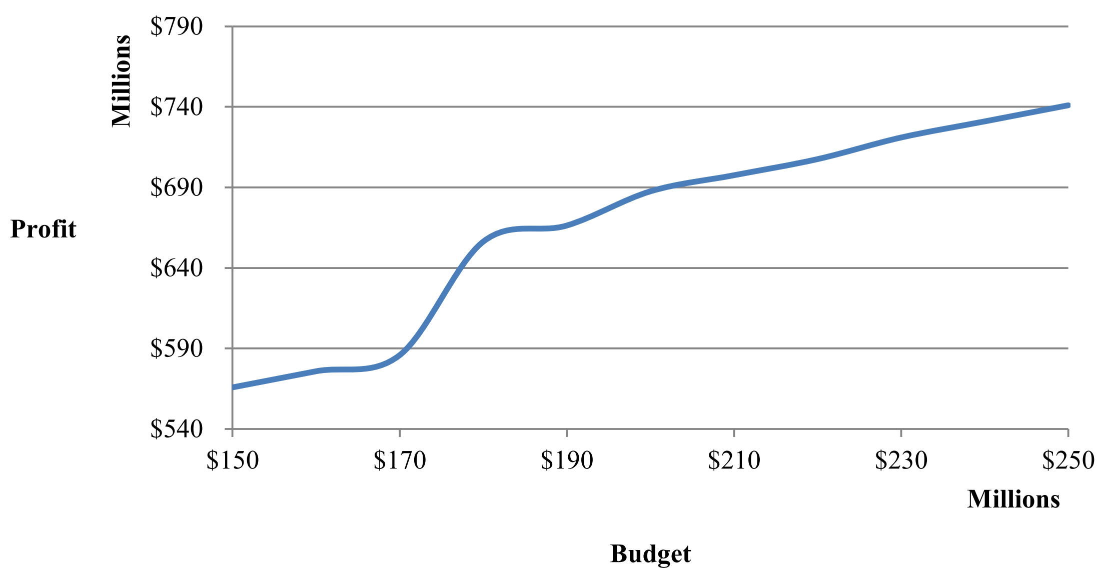


Figure 19 Sensitivity analysis of profit to the initial development budget

In general, the model gives a forecast of the maximum profit of the product family that should be introduced to market over the expected time period. Also, it gives some useful information about the potential demand of each type of product and the amount of products that should be recycled in upcoming years. In the numerical example, the expected time is four years. Also, it shows the level of greenness for each product in each period in order to reach maximum benefit for the company. At the end, two sensitivity analyses are done to evaluate the behavior of the model when the original data of some parameters are changed. This information gives managers have a view of the effect of different parameters on a product's demand and the project's profit in the future.

5. Conclusions, limitations, and opportunities for future research

In this chapter, conclusions of the research, limitations, and future research opportunities are discussed.

5.1 Conclusions

Firms are encouraged to develop a new generation of products, i.e. green products, to avoid harmful impacts of their current design and manufacturing processes on the environment. However, the future financial effect of green products is the main concern of managers in charge of new product development (NPD) projects. Business analysis is one of the most important stages of NPD that shows the perspective of new products after launching in the market. Precise financial analysis of a product in this stage equips decision makers with proper forecasts of the product.

In this thesis, a comprehensive model is proposed for analyzing the trade-off between potential costs and revenues in environmental friendly products, which are designed based on recyclability, disassembly, and an environmentally friendly disposal strategy. First, a primary mixed integer model is designed based on cost and revenue parameters throughout the product life cycle, from development to disposal. The model's constraints present some major limitations that companies are facing in their production and recycling processes, in addition to effects of these limitations on economical parameters. The crucial point of this model is the consideration of product development and recycling costs in addition to manufacturing cost, which affects the managers' decision in the production process. Also, we attempted to reflect different aspects of typical problems that companies are faced with in production and recycling processes such as: machine and labor limitations, and carbon tax.

A generalized model has been designed so that it is applicable in many CPG manufacturers such as electronics, toy, and furniture industries. It can help managers to calculate the optimum production and recycling amount of the product, with respect to the factory's throughput, to reach the maximum profit. Also, it releases very useful information about the amount of emission produced in product manufacturing and recycling processes. Managers can compare this information with the current situation of the product and decide about the continuation of the product development project. A numerical example, in the electronic appliance industry, is presented in order to show how a manager can use the model's results. The primary model's parameters are divided into three main parts: development and production, CO_2 emission, and recycling. Development, manufacturing, assembly, and material costs are identified as basic parameters in development and production. Also, disassembly, shredding, recovery, and disposal costs are defined as fundamental parameters of recycling a product. Finally we considered two different parameters (emission produced for producing and emission produced for recycling) to measure total CO_2 emission tax in stepwise model. The primary model makes two main contributions: on the theoretical side, we offer a comprehensive model for analyzing the trade-off between profitability and recyclability, disassembly, and environmentally friendly disposal attributes of green products in all stages of the product life-cycle. On the managerial side, it provides a decision support methodology for management in order to decide about the future of an NPD project in the design stage.

The primary model is further developed using dynamic programming approach. A dynamic model is proposed to help decision makers to forecast the profit of a family of products, which is designed based on recyclability, disassembly, and an environmentally friendly disposal strategy, based on each product's cash flow in its life-cycle. The model is designed for a product, such as an automobile, that different generation that can be introduced to the market in each period. We assumed different level of greenness for a car that can be produced and introduced to the market. According to the model, a company can schedule the process of development of products to reach maximum profit in a given time. Thus, the model helps managers to identify accurate policy to introduce a new product with different level of greenness to the market according to the company's R&D budget constraint in each time. In addition, managers can estimate the demand of each class of products based on selected policy in each period. A numerical example, in the automotive industry, is defined in order to show how the model works and how managers can use from the model's results. The dynamic model's variables are divided into two main parts: state and decision variables. Level of greenness in each vehicle and available R&D budget in each period are identified as state variables. Also, a binary variable is defined to make a decision about the levels have to be completed in each vehicle. Finally the nested logit model, which is an appropriate model of GEV models, is used to model the demand of each product based on the consumers' utility function. The utility function parameters can be defined based on product specifications and target market attributes. In this model, the consumer's average income, the product's price, average operation cost and the degree of sensitivity to environment in a consumer are considered as main parameters which affect the consumer's demand of sustainable products in the automotive industry. The dynamic model also makes two main contributions: on the theoretical side, we offer a comprehensive model for analyzing the profit of a group of products with the same attributes, while the full green generation of all products have to be introduced to the market after a given period time. Also, it shows the interaction between the level of environmental performance and demand on green products in the automotive industry. On the managerial side, it provides a decision support methodology for decision makers to analyze the new green product's profitability and demand in the business analysis stage of NPD process.

5.2 Limitations and future research

The model's limitations can be categorized into conceptual and technical levels. On the conceptual side, the model has some limitations such as: it cannot calculate the net profit of the recycling process separately. Also, logistic costs (such as warehouse or collection center for recycling) are not considered in this model, although it can have an effect on profit in some industries. In addition, it does not consider actions and reactions of competitors against a company's decisions. Next, the technology change effects are not considered. Moreover, the risk of each outcome is not reflected in the process. On the technical side, curse of dimensionality is a main limitation of dynamic programming. Thus, coding and solving of the dynamic model were two technical limitations of our research. Eventually, to calculate the demand of each vehicle in reality, many parameters such as education, age, sex etc. can affect the consumer's utility function.

For future investigation, the model can be:

1. Developed by considering technology and competitors' effects on the probability of new product success. Thus, the model has to be formulated based on infinite horizon dynamic programming and dynamic game models.
2. Applied for each step of a new green product development according to minimum development cost or time.
3. Customized for other industries (i.e. dairy industry, aerospace) to find green product development process and calculation of emission tax.

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Appendix A: Inputs for the first numerical example (Blender)

Parameter	Cost ($)	Scale	Parameter	Cost ($)	Scale	Parameter	Cost ($)	Scale	Parameter	Cost ($)	Scale
P_s	40	Per unit	U_1	0.078	Per unit	$C_{a_{13}}$	0.5	Per unit	R_{64}	0.03	Per unit
P_{u_1}	1.578	Per unit	U_2	0.13	Per unit	$C_{a_{16}}$	0.5	Per unit	l_{r_1}	0.04	Per tonne
P_{u_2}	1.53	Per unit	U_3	0.322	Per unit	$C_{a_{21}}$	0.85	Per unit	l_{r_2}	0.07	Per tonne
P_{u_3}	2.672	Per unit	U_4	0.018	Per unit	$C_{a_{35}}$	0.84	Per unit	l_{r_3}	0.01	Per tonne
P_{u_4}	2.238	Per unit	U_5	0.129	Per unit	$C_{a_{46}}$	0.53	Per unit	l_{r_4}	0.05	Per tonne
P_{u_5}	1.159	Per unit	U_6	0.108	Per unit	$C_{a_{57}}$	0.73	Per unit	W_{r_1}	0.004	Per tonne
P_{u_6}	1.038	Per unit	U_7	0.1185	Per unit	C_{sh_1}	0.0002	Per unit	W_{r_2}	0.006	Per tonne
P_{u_7}	0.2385	Per unit	C_{mfct_1}	1	Per unit	C_{sh_2}	0.0003	Per unit	W_{r_3}	0.009	Per tonne
P_{m_1}	0.078	Per tonne	C_{mfct_2}	0.9	Per unit	C_{sh_4}	0.0006	Per unit	W_{r_4}	0.019	Per tonne
P_{m_2}	0.075	Per tonne	C_{mfct_3}	1.5	Per unit	R_{31}	0.0104	Per unit	d_c	0.02	Per tonne
P_{m_3}	0.06	Per tonne	C_{mfct_4}	1.38	Per unit	R_{32}	0.045	Per unit	W_d	0.053	Per tonne
P_{m_4}	0.186	Per tonne	C_{mfct_5}	0.5	Per unit	R_{53}	0.012	Per unit	T_1	0.21	Per kilogram
D_c	100000	-	C_{mfct_6}	0.2	Per unit	R_{54}	0.027	Per unit	T_2	0.26	Per kilogram
C_d	5	Per unit	C_{mfct_7}	0.12	Per unit	R_{63}	0.0015	Per unit	T_3	0.32	Per kilogram

Parameter	Amount	Scale	Parameter	Amount	Scale	Parameter	Amount	Scale	Parameter	Amount	Scale
ϑ	962	hours per week	$\emptyset_{46}$	0.007	kilogram	F	0.36	kilogram	σ_5	48	Sec.
t_{12}	10	Sec.	$\emptyset_{57}$	0.09	kilogram	O_r	50	kilogram	σ_6	10	Sec.
t_{13}	25	Sec.	δ_{21}	19	Sec.	φ_1	5.79	hours per day	σ_7	12	Sec.
t_{16}	31	Sec.	δ_{22}	12	Sec.	φ_2	5.18	hours per day	E_1	20000	kilogram
t_{35}	12	Sec.	δ_{31}	21	Sec.	φ_3	5.34	hours per day	E_2	30000	kilogram
t_{46}	8	Sec.	δ_{32}	16	Sec.	φ_4	5.26	hours per day	E_3	400000	kilogram
t_{57}	27	Sec.	δ_{43}	5	Sec.	φ_5	9615	Kilogram per week	α	0.4	-
e_1	0.017	kilogram	δ_{44}	9	Sec.	φ_6	7500	Kilogram per week	L_a	2991	hours per week
e_2	0.014	kilogram	δ_{53}	4	Sec.	β_{12}	10	Sec.	δ_{11}	12	Sec.
e_3	0.027	kilogram	δ_{54}	10	Sec.	β_{13}	25	Sec.	δ_{12}	5	Sec.
e_4	0.09	kilogram	δ_{63}	3	Sec.	β_{16}	31	Sec.	d_1	22000	product
e_5	0.0175	kilogram	δ_{64}	1	Sec.	β_{35}	12	Sec.	d_2	20000	product
e_6	0.027	kilogram	δ_{73}	1	Sec.	β_{46}	8	Sec.	d_3	18000	product
e_7	0.1	kilogram	δ_{74}	1	Sec.	β_{57}	27	Sec.	d_4	10500	product
$\emptyset_{12}$	0.012	kilogram	W_{15}	0.03	kilogram	σ_1	20	Sec.			
$\emptyset_{13}$	0.017	kilogram	W_{25}	0.05	kilogram	σ_2	16	Sec.	h	5	product
$\emptyset_{16}$	0.012	kilogram	W_{46}	0.012	kilogram	σ_3	29	Sec.	g	10	product
$\emptyset_{35}$	0.016	kilogram	O_p	1000	kilogram	σ_4	39	Sec.	τ	1	year

Appendix B: CPLEX outputs for the first numerical example (Blender)

Problems | Solutions | Conflicts | Relaxations | Engine log | Statistics | Profiler | CPLEX Servers

```
// solution (optimal) with objective 2383264.1998
// Quality Incumbent solution:
// MILP objective                                  2.3832641998e+006
// MILP solution norm |x| (Total, Max)             3.35439e+005 1.00000e+005
// MILP solution error (Ax=b) (Total, Max)         6.11049e-008 3.05154e-008
// MILP x bound error (Total, Max)                 0.00000e+000 0.00000e+000
// MILP x integrality error (Total, Max)           0.00000e+000 0.00000e+000
// MILP slack bound error (Total, Max)             7.27596e-012 7.27596e-012
//

x = [20769
         20769 20769 20769];
y = [0 8307 7815 7200];
I = [0 0 2307 12876];
B = [1231 462 0 0];
Psi = [0 0 37386];
Epro = [7626.8 7032.9 7068.1 7112];
Mu1 = [1 1 1 1];
Erecy = [0 3040.5 2863.4 2642];
Mu2 = [0 1 1 1];
Eco2 = 37386;
Eta = [0 0 1];
```

Problems | Solutions | Conflicts | Relaxations | Engine log | Statistics | Profiler | CPLEX Servers

```
// solution (optimal) with objective 2251997.6788
// Quality Incumbent solution:
// MILP objective                                  2.2519976788e+006
// MILP solution norm |x| (Total, Max)             2.91479e+005 1.00000e+005
// MILP solution error (Ax=b) (Total, Max)         1.22070e-006 6.10351e-007
// MILP x bound error (Total, Max)                 0.00000e+000 0.00000e+000
// MILP x integrality error (Total, Max)           0.00000e+000 0.00000e+000
// MILP slack bound error (Total, Max)             0.00000e+000 0.00000e+000
//

x = [20769
         20769 20769 20769];
y = [0 0 0 0];
I = [0 0 2307 12876];
B = [1231 462 0 0];
Psi = [0 0 30507];
Epro = [7626.8 7626.8 7626.8 7626.8];
Mu1 = [1 1 1 1];
Erecy = [0 0 0 0];
Mu2 = [0 0 0 0];
Eco2 = 30507;
Eta = [0 0 1];
```

Appendix C: Inputs for the second numerical example (Automotive)

A part of following data is generated based on the information that is presented by the U.S. department of energy (U.S. Department of Energy's Clean Cities program, 2015). Also, "Production and Logistic Costs", and "Warranty and other Costs" for each product are generated based on realistic case in the litreature (i.e. Lipman, T. E., & Delucchi, M. A. ,2006).

Car Model	Sub-Model	Price ($)	Production and logistic Costs ($)	Warranty and other Costs ($)	Recycling Revenue ($)	Recycling Cost ($)	Average Maintenance Cost ($)	Annual Fuel Cost ($)	Annual Emission (lbs CO_2)
A	A-1	18027	10795	6836	0	0	3414	1114	8271
	A-2	19357	11591	7072	2318	2086	3228	1114	8271
	A-3	20788	12374	7883	3712	2970	3202	815	6042
	A-4	21200	12619	8154	2659	2128	3073	815	5026
B	B-1	20450	12246	7755	0	0	3406	1105	8201
	B-2	22645	13560	8587	2712	2441	3294	1105	8201
	B-3	23838	14189	9040	4257	3405	3289	808	5991
	B-4	24050	14315	9250	3050	2135	3066	808	5089
C	C-1	22704	13595	8610	0	0	3569	1307	9697
	C-2	24173	14475	9167	2895	2605	3325	1307	9697
	C-3	26587	15826	10226	4748	3798	3239	956	7084
	C-4	26700	15893	10269	3401	2721	3213	956	5580

Development cost for each product	Level 1	Level 2	Level 3	Level 4
Level 1	0	50000000	75000000	100000000
Level 2	0	0	25000000	50000000
Level 3	0	0	0	25000000
Level 4	0	0	0	0

Environment Preference	Level 1	Level 2	Level 3	Level 4
Product A	4693.209	4693.209	3428.5	2920.5
Product B	4653.5115	4653.5115	3399.5	2948.5
Product C	5502.902	5502.902	4020	3268

Average Salary	Coefficient of Salary	Coefficient of Price	Coefficient of Maintenance	Coefficient of Environment Preference	Coefficient of other unobserved variables	λ_1	λ_2	β	Discount Factor
52,000	0.5002	-0.80131	-0.40397	-0.62159	-5	0.6	1	20%	0.99