แบบจำลองการตัดสินใจโดยมีการเชื่อมโยงกับการประเมินวัฏจักรชีวิตเพื่อความเหมาะสมในการแปรรูปหลอดฟลูออเรสเซนท์ที่ใช้แล้วในกรุงเทพมหานครและพื้นที่ใกล้เคียง

นาย วิฑูรย์ อภิสิทธิ์ภูวกุล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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A DECISION-MAKING MODEL INCORPORATING THE LIFE CYCLE ASSESSMENT FOR THE OPTIMAL RECYCLING OF SPENT FLUORESCENT LAMPS IN BANGKOK AND THE VICINITY

Mr.Witoon Apisitpuvakul

A Dissertation Submitted in Partial Fulfillment of the Requirements
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Thesis Title	A DECISION-MAKING MODEL INCORPORATING THE LIFE CYCLE ASSESSMENT FOR THE OPTIMAL RECYCLING OF SPENT FLUORESCENT LAMPS IN BANGKOK AND THE VICINITY
By	Mr. Witoon Apisitpuvakul
Field of study	Environmental Management
Thesis Advisor	Assistant Professor Woranut Koetsinchai, Ph.D.
Thesis Co-advisor	Associate Professor Pornpote Piumsomboon, Ph. D.

Accepted by the Graduate School, Chulalongkorn University in Partial Fulfillment of the Requirements for the Doctoral Degree

Vice President
....Acting Dean of the Graduate School
(Assistant Professor M.R. Kalaya Tingsabadh, Ph.D.)

THESIS COMMITTEE

....Chairman
(Assistant Professor Manasakorn Rachakornkij, Ph.D.)

....Thesis Advisor
(Assistant Professor Woranut Koetsinchai, Ph.D.)

....Thesis Co-advisor
(Associate Professor Pornpote Piumsomboon, Ph.D.)

W. Wirojanagud
....Member
(Associate Professor Wanpen Wirojanagud, Ph.D.)

Netnapid Tantemsapya
....Member
(Assistant Professor Netnapid Tantemsapya, Ph.D.)

....Member
(Assistant Professor Sompop Sanongraj, Ph.D.)

วิฑูรย์ อภิสิทธิ์ภูวกุล : แบบจำลองการตัดสินใจโดยมีการเชื่อมโยงกับการประเมินวัฏจักรชีวิตเพื่อความเหมาะสมในการแปรรูปหลอดฟลูออเรสเซนท์ที่ใช้แล้วในกรุงเทพมหานครและพื้นที่ใกล้เคียง (A DECISION-MAKING MODEL INCORPORATING THE LIFE CYCLE ASSESSMENT FOR THE OPTIMAL RECYCLING OF SPENT FLUORESCENT LAMPS IN BANGKOK AND THE VICINITY) อ. ที่ปรึกษา : ผศ. ดร. วรนุช เกิดสินธ์ชัย, อ.ที่ปรึกษาร่วม : รศ.ดร.พรพจน์ เปี่ยมสมบูรณ์ จำนวน 154 หน้า.

หลอดฟลูออเรสเซ็นต์ที่ใช้แล้วเป็นผลิตภัณฑ์ชนิดหนึ่งที่สามารถนำมาแปรรูปได้ โดยใช้เทคโนโลยีแบบพิเศษเนื่องจากมีปรอทพิษผสมอยู่ จากการศึกษาของกรมควบคุมมลพิษในปี 2004 ชี้ให้เห็นว่าปริมาณหลอดฟลูออเรสเซ็นต์ที่ใช้แล้วถูกทิ้งในประเทศไทยมีประมาณ 45 ล้านหลอดต่อปี ประกอบกับความต้องการใช้หลอดฟลูออเรสเซ็นต์มีแนวโน้มเพิ่มขึ้นตามอัตราการเจริญเติบโตของประชากรและการเจริญเติบโตของเศรษฐกิจ ดังนั้น การวางแผนแปรรูปหลอดที่ใช้แล้วอย่างเหมาะสมในอนาคตนับเป็นสิ่งสำคัญ เพราะถ้าสถานที่ตั้งของโรงงานแปรรูป อัตราส่วนร้อยละของการแปรรูป ความจุของโรงงานแปรรูปถูกออกแบบอย่างไม่เหมาะสม จะมีการใช้วัตถุดิบและพลังงานในการแปรรูปมากและก่อให้เกิดผลกระทบทางสิ่งแวดล้อมในวงจรชีวิตของผลิตภัณฑ์มาก อย่างไรก็ตามปัญหาหลักคือ การหาการตัดสินใจที่เหมาะสมเพื่อการแปรรูปหลอดหลอดฟลูออเรสเซ็นต์ที่ใช้ ซึ่งเป็นปัญหาที่ซับซ้อน เพื่อเป็นการช่วยผู้ที่ตัดสินใจแก้ปัญหา แบบจำลองการตัดสินใจเพื่อความเหมาะสมในการแปรรูปหลอดฟลูออเรสเซ็นต์ที่ใช้แล้วได้ถูกพัฒนาขึ้นเพื่อการศึกษาในครั้งนี้ วัตถุประสงค์ของแบบจำลองคือเพื่อทำให้ค่าผลกระทบที่เกิดขึ้นจากกิจกรรมต่างในวงจรชีวิตของการแปรรูปหลอดฟลูออเรสเซ็นต์ที่ใช้แล้วมีค่าต่ำที่สุด เหมาะกับงบประมาณที่ตั้งไว้ ตัวแบบจำลองนี้จะหาค่าอัตราร้อยละของการแปรูปที่เหมาะสม จุดที่ตั้งขยายโรงงานแปรรูปได้ในแต่ละปี ขนาดความจุที่เหมาะสมในการก่อสร้าง ซึ่งผู้ตัดสินใจสามารถนำไปใช้ในการวางนโยบาย ในการจัดการของเสียคือหลอดฟลูออเรสเซ็นต์ที่ใช้แล้ว ในทุกกิจกรรมที่เกี่ยวข้อง เพื่อที่จะปรับปรุงคุณภาพสิ่งแวดล้อมในงบประมาณที่จำกัด วิธีการศึกษาเริ่มจากการให้รายละเอียดแผนผังการไหลของทุกกิจกรรมและเทคโนโลยีที่เกี่ยวข้องสำหรับจัดการหลอด การวิเคราะห์รายการวัตถุและพลังงาน การประเมินผลกระทบสิ่งแวดล้อม รวมถึงทำการพัฒนาแบบจำลองค่าใช้จ่ายและผลตอบแทนที่ได้รับ จากนั้นจึงพัฒนาตัวแบบที่ใช้ในการตัดสินใจ โดยเชื่อมทุกตัวแบบเข้าด้วยกัน ระเบียบขั้นตอนทางคณิตศาสตร์และการสร้างตัวแบบในโปรมแกรมคอมพิวเตอร์ถูกเขียนอย่างซับซ้อน ในขณะที่ข้อมูลค่าคงที่ที่ถูกป้อนเข้าในแบบจำลองถูกเตรียม และจุดที่จะตั้งโรงงานแปรรูปถูกกำหนด สำหรับพื้นที่ศึกษาในที่นี้คือกรุงเทพมหานครและจังหวัดโดยรอบ จากนั้นทำการสำรวจแบบจำลอง และตรวจหาค่าที่เหมาะสมในการแปรรูปหลอดที่ใช้แล้วในพื้นที่ศึกษา ผลการศึกษาในพื้นที่ศึกษาชี้ให้เห็นว่า อัตราร้อยละของความเหมาะสมในการแปรรูปหลอดที่ใช้แล้วมีค่าอยู่ระหว่าง 85% - 89% ในช่วงเวลาการแปรรูปอีก 20 ปี สถานที่ในการตั้งโรงงานมี 2 แห่ง ได้แก่ และสมุทรปราการ และปทุมธานี โรงงานแห่งแรกจะต้องขยายโรงงานแปรรูปเป็น 33 หน่วย (1 หน่วยรองรับการแปรรูปหลอดที่ใช้แล้วได้ 1,269,000 หลอด) ในขณะที่จุดสองต้องขยายให้เป็นทั้งหมด 2 หน่วยในระยะเวลา 20 ปี ในขณะที่ผลกระทบด้านสิ่งแวดล้อม ที่เกิดจากการตัดสินใจครั้งนี้มีค่าต่ำสุดเท่ากับ 1,549,315,401 หน่วยและมูลค่าปัจจุบันสำหรับผลประโยชน์ที่ได้รับโครงการทั้งหมดมีค่ามากกว่าค่าใช้จ่าย 8,482,510 บาท

สาขาวิชาการจัดการสิ่งแวดล้อม
ปีการศึกษา 2550

ลายมือชื่อนิสิต Witoon A
ลายมือชื่ออาจารย์ที่ปรึกษา
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม

468 97126 20 : MAJOR ENVIRONMENTAL MANAGEMENT
KEY WORD: SPENT FLUORESCENT LAMPS/RECYCLING/OPTIMIZATION
LIFE CYCLE ASSESSMENT
WITOON APISITPUVAKUL: A DECISION-MAKING MODEL INCORPORATING THE LIFE CYCLE ASSESSMENT FOR THE OPTIMAL RECYCLING OF SPENT FLUORESCENT LAMPS IN BANGKOK AND THE VICINITY. THESIS ADVISOR: Assist. Prof. Woranut Koetsinchai, Ph.D.
THESIS COADVISOR: Assoc. Prof. Pornpote Piumsomboon, Ph.D. 154 pp.

Spent fluorescent lamps (SFLs) are a product that must be recycled by using special technology because fluorescent lamps (FLs) contain toxic elemental mercury. A study of the Pollution Control Department (PCD) in 2004 indicated that SFLs discarded in Thailand include approximately forty-five million lamps per year. The study also suggested that the demand for fluorescent lamps was growing due to the population growth and economic development. Proper recycling planning for used lamps in the future is thus important. If the location sites for the recycling plants, percents of recycling and the capacity of the recycling plants are not properly designed, it will consume high levels of energy, materials and cost, and generate high environmental impacts from the life cycle of the product. A main problem, however, is making the optimum decision for the recycling of SFLs which is a complicated problem. To solve this problem, a decision-making model for creating the optimal plan for the recycling of SFLs was developed in this study as a tool for decision makers. The objective of the model was to minimize the environmental impact arising from significant activities in the life cycle of the recycling of SFLs while meeting budget constraints. The model determined what the optimal percents of recycling are, where the best possible locations for building recycling plant expansions would be, as well as what the optimal capacity of a recycling plant expansion is. This will be useful for policy-makers in setting up a national policy of waste management arising from SFLs for improving the global environmental quality under a controlled budget. The procedure was started with a detailed process flowchart of all concerned activities for available technology used to manage SFLs, then an inventory analysis was done, and all concerned models including those for inventory, environmental impact and cost –benefit, were prepared. Finally, a decision making model was developed from the linkage of all these concern models together. A complex algorithm was also written and the computer model formulation was done. While their model input parameter values were collected, hypothetical recycling plants were also specified for the case study areas including Bangkok and surrounding provinces in Thailand. Model explorations were done, while the optimum results for SFL planning in the case study areas were investigated. The results indicated that the optimum recycling percentages in the study areas were in the range of 85% - 89% with a 20 year planning horizon. Following the requirements for the recycling plants, 2 locations were indicated. The first one was located in Samutprakarn province and the second, in Pathumthani province. The first location was required for 33 units in the recycling plant (one unit can recycle 1,269,000 SFLs), while the other was required for 2 units. As a result,, the total environmental impact was minimized to 1,549,315,401 units (in a single score unit), while the net present value (NPV) of benefit was more than the NPV of cost at about 8,482,510 Baht.

Field of Study Environmental Management Student's study signature......Witoon A.......
Academic year 2007 Advisor's signature..
Co-advisor's signature..

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LIST OF ABBREVIATIONS

FL = Fluorescent Lamp
FLs = Fluorescent Lamps
SFL = Spent Fluorescent Lamp
SFLs = Spent Fluorescent Lamps
LCA = Life Cycle Assessment
DALY = Disability adjusted life years; this refers to the calculated years spent with different disabilities caused by diseases
PDF = Potentially Disappeared Fraction of plant species
MJ surplus = Additional energy requirement to extract a kg of a mineral in the future
B = Base case of a model
ROG = Rate of Growth
IR = Interest Rate
IF = Inflation Rate

CHAPTER I

INTRODUCTION

1.1 Rationale for the study

End-use product recycling is one approach of waste management that can reduce the emission of wastes into the environment (i.e. a reduction in landfill areas). The recycling scheme can reduce the consumption of refined materials (saving resources) and energy used for new material extraction, since recycled materials can be recovered to be used again. Recycling thus helps improve environmental performance throughout the end-use product life cycle. At the same time, it generates market value from the selling of recovered materials, which is unlike landfilling. On the contrary, recycling processes consume materials and energy throughout the entire life cycle chain, starting from transportation, disassembly at recycling plants, treatment of wastes emitted during the recycling processes and ultimate residual waste disposal, respectively. Therefore, several relative questions arise, such as whether to recycle or use a landfill. If we choose recycling, then what should the optimal recycling rate be? Should we be building recycling plants each year? Finally, where should they be built and to what capacity?

The solutions to these problems encompass two challenges in ingenuity. The first challenge stems from the physical complexities and dimensionality of the problems. Recycling of spent fluorescent lamps (SFLs) requires a special technology and a number of processes throughout the entire recycling chain. The total costs incurred during the stages of the recycling processes are thus high. Moreover, the capacity expansion of recycling plants requires a lumpy investment while the budget is limited. Most importantly, end-used products induce high levels of environmental impacts because fluorescent lamps (FLs) contain significant quantities of the toxic element mercury. A study of the Pollution Control Department (PCD) in 2004 indicated that the quantity of SFLs discarded in Thailand is approximately forty-five million lamps per year. The study also suggested that the demand for fluorescent lamps was growing due to the population growth and economic development. The growing fluorescent demand increases the amount of end-used fluorescent lamps and hence, an increasingly deteriorating environment. As a result of these aspects, it is necessary to decide on how to manage end-used fluorescent lamps and on how the sensitivity of the decision feedbacks to the growth of the fluorescent demand. Such decision-making is complicated and requires a systematic way to determine the optimal policy. If a recycling policy illustrated by the rate of recycling and capacity of recycling plants as well as location sites for the expanded recycling plants is not properly designed, it will result in high energy and materials consumptions and finally, in high global environmental impacts. A decision-making model for determining the optimal recycling policy is thus important.

The second challenge arises from computational complexity. A mathematical model is necessary for the problem with the above aspects characterized as a dynamic mixed-integer programming problem. This kind of problem is generally difficult to solve. Several “off-the-shelf” volumes are usually promising an optimal solution using only the first and second specifications. Although global optimization remedies are currently available in several “off-the-shelf” volumes, those practically cannot guarantee the optimal global solution, especially for large scale problems. As a result, a decision-making model incorporating a life cycle assessment for the optimal recycling of spent fluorescent lamps is important and challenges the ingenuity.

1.2 Research Objectives

The overall objectives of this dissertation are summarized as follows:

1. To conduct an environmental impact assessment of spent fluorescent lamp recycling using a life cycle assessment (LCA) approach.
2. To develop a decision-making model which determines the optimal policy for the recycling of Spent Fluorescent Lamps (SFLs) over a specified planning horizon. It should include the recycling rate and capacity of a regional recycling plant as well as, location site, while environmental impacts incurred over the life cycle of Fluorescent Lamps (FLs) are minimized subject to cost-benefit constraints.
3. To apply the model to optimal planning for recycling the used fluorescent tubes generated in Bangkok and the vicinity.

1.3 Scope of the study

The goal of this study is to minimize the global environmental impacts due to the life cycle of the recycling of used fluorescent tubes generated in Bangkok and the vicinity subject to budget constraints. The recycling material was confined to mercury which is a highly toxic element. In this study, it is assumed that there are presently no fluorescent recycling plants and two hypothetical plants will be built in Samutprakarn province and in Pathumthani province within a 20-year planning horizon. In addition, a hypothetical landfill will be located in Ratchaburi province. Various scenarios of growth rates of fluorescent lamp consumption, interest rates and inflation rates were used to conduct sensitivity analyses of the model solutions.

1.4 Framework of the dissertation

In this dissertation, an optimization model incorporating a management and cost-benefit models was formulated as a mixed-integer dynamic programming model. The global environmental impact model with linkage to waste management policies was mathematically formulated based upon a life cycle assessment approach.

The waste management policy options used in this dissertation study are those for determining whether or not to recycle spent fluorescent, or to landfill. If recycling is decided upon, then, what should the recycling rates be, where should the sites for recycling plants be located, and whether the capacities of hypothetical recycling plants should be expanded and, if so, how much.

The environmental impacts taken into consideration include health and ecosystem impacts as well as resource depletion. The cost model includes costs arising from activities throughout all stages of recycling and disposal as well as resource production chains.

Initially, the recycling and disposal process chains throughout the spent fluorescent lamp life cycle, as well as, materials and energy production systems, as depicted in System I and II (Figure 1.1) respectively, were analyzed. The amounts of material and energy consumption, pollutant emission incurred by activities during all stages of recycling and disposal, as well as, resource production chains were then estimated using secondary data obtained from existing disposal plants in Thailand. Thereafter, the impacts on the natural environment measured by the amount of natural resources depletion and of pollutant emission to natural environment were examined based upon the Eco-indicator 99 (I) V2.1 method. The resource depletion is determined by the reduction in minerals which is a material for energy production. The eco-indicators determining the impacts of pollutant emission on the eco-system were composed of ecotoxicity, acidification/eutrophication and land use. Additionally, carcinogens, respiratory organics and inorganics, climate change, radiation and the ozone layer were the eco-indicators utilized for assessing health impacts. The results of these environmental impact assessments were utilized to create an objective function of a minimization model with linkage to management policies.

Next, the cost arising from activities in recycling and disposals as well as resource production process chains were collected using secondary data obtained from existing disposal plants in Thailand. The costs of recycling were estimated from those incurred during transportation and disassembly processes as well as waste disposal. Finally, benefits taken into account consist of incomes generated from selling recovered materials and the revenue obtained from the SFL disposal fee. The costs and benefits obtained were employed to formulate benefit constraints.

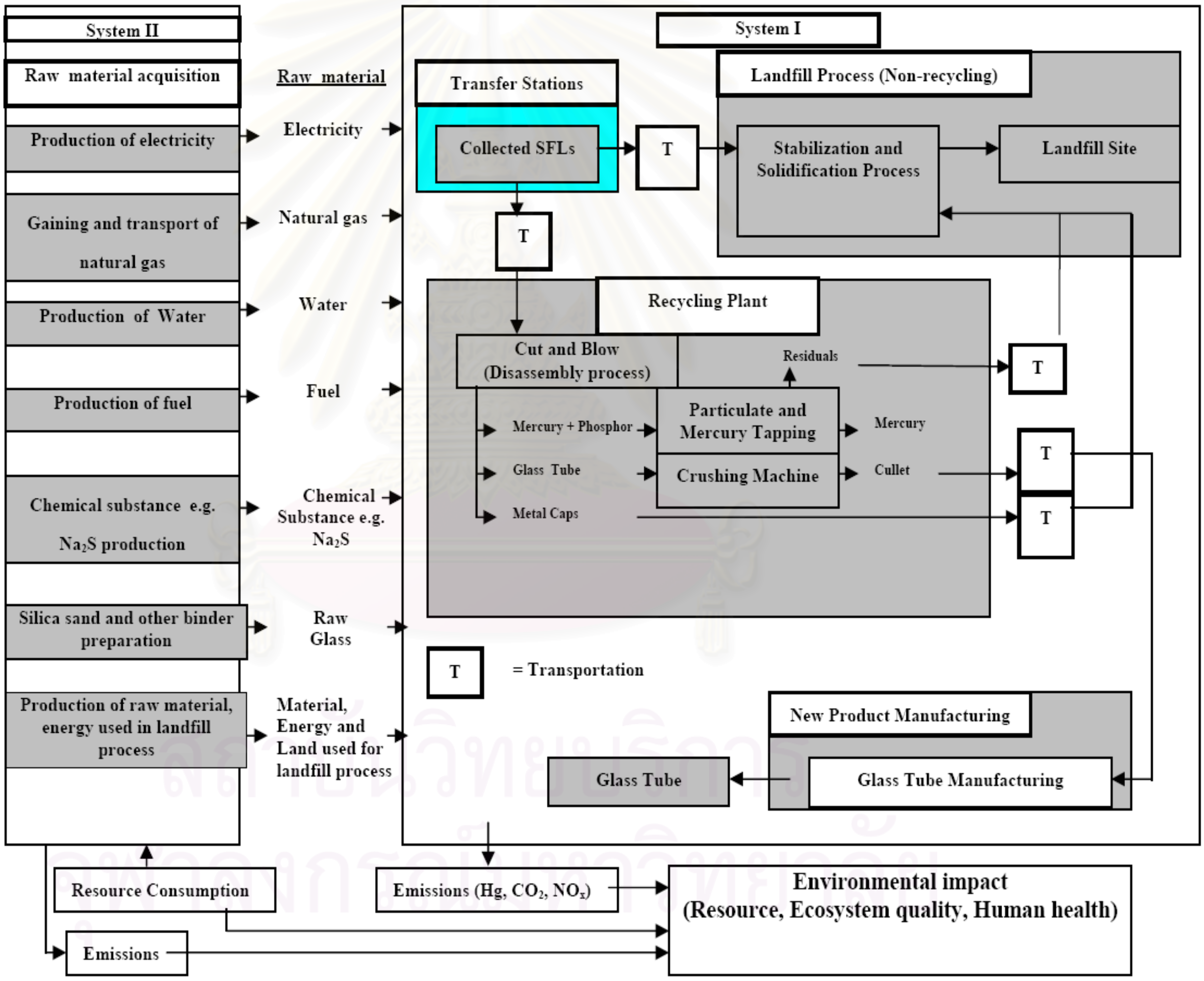


Figure 1.1 A schematic overview of all activities of concern within the boundary established for SFL recycling.

1.5 Contribution to knowledge

Traditional environmental waste management problems have usually been decided by rules of thumb, otherwise, by comparing various alternative policies to reduce environmental impacts, under government budget constraints. Although currently, several researchers and policy-makers have recognized LCA as an effective tool for the systematic evaluation of the environmental aspects of a product or service system through the “cradle to grave” life cycle, it is not devised for assisting policy makers in selecting the optimal waste management program. On the contrary, the LCA, dealing only with environmental impacts assessment associated with a given waste management policy, has no direct linkage to management options. These may result in an environmental waste management program that is not comprehensive. Hence, it will be helpful to develop a generalized model that combines both environmental waste management and associated impact models. This dissertation has introduced a new systematic decision-making model for determining the optimal recycling policy of spent fluorescent lamps. The model incorporates management policies and global environmental impacts as well as budget constraints to attain the optimal waste management policy while meeting given budget constraints. The work can serve as a decision making tool for future waste management projects.

1.6 Organization of the Study

Chapter II provides the literature reviews of the study. In this chapter, all required background data and other related works for LCA and a decision making model for waste management were reviewed. Initially, the components of SFLs, the situation of generated SFLs, and existing technology for the disposal of SFLs were reviewed, respectively. Then, the theoretical background of a life cycle assessment (LCA) was explained incorporating the history in waste management model. Finally, the optimization theory and the algorithms used in the model development were reviewed.

In Chapter III, in order to achieve the dissertation’s goals, the methodology applied in this study was declared starting with the life cycle assessment principle used to develop the inventory model as part of the inventory analysis. Thereafter, the output data from the inventory model which consisted of the amount of materials and energy including the released pollutants as well as recovery materials would be inputted into the environmental impact analysis model to define the environmental impact burden. Also costs and benefits generated were modeled. Then, by linking all the models together, the decision making model was defined and formulated on an excel spreadsheet. All required input data was collected for a case study area and inputted into the model for testing. Finally, the ouput model results were discussed and concluded.

CHAPTER IV provided the results of data on the socio-economic aspects which were collected from a case study area, involving Bangkok and the vicinity. The data obtained in this part consisted of the load of SFLs generated incorporating the rate of SFL growth. The locations of each hypothetical recycling plant and non-recycling plant were declared. Also, the distance data between each node was provided.

CHAPTER V provided the mathematic model formulations. These show the relationships between all the concerned decision variables and model input parameters. The models declared in this chapter were composed of an inventory model, environmental impact assessment model, cost and benefit model, and decision making model, respectively. Also, all required model input data was indicated.

CHAPTER VI, after all model input data was inputted into the model, all model output results were indicated and discussed in this chapter by dividing them into two parts. The first part is the results of a life cycle assessment of the recycling of SFLs at various recycling rates. The second part includes the optimum SFL recycling results for a case study area.

In CHAPTER VII, all the results were concluded and the possibilities for future works were presented.

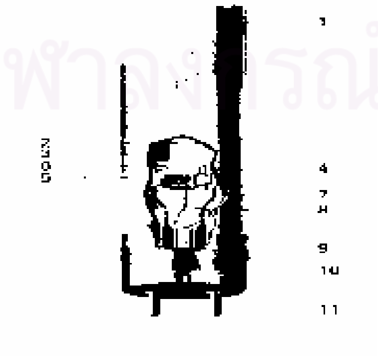
CHAPTER II

LITERATURE REVIEW

To develop a decision making model for producing the optimal SFL recycling policy, data and information regarding the current management of SFL disposal, background knowledge of fluorescent lamps, as well as, state-of-the art technology to recycle the fluorescent bulbs are required. Specifically, it is necessary to understand the life cycle assessment principles and basic concepts related to optimization employed for producing the optimal SFL recycling policy. Therefore, in this chapter, the components of SFLs, the situation on generated SFLs and their disposal, as well as, existing technology for FL disposal were initially reviewed. Then, the theoretical background of the life cycle assessment (LCA) and research related to waste management models were explained. Finally, basic concepts of optimization were described.

2.1 The component of spent fluorescent lamps (SFLs)

Spent fluorescent lamps (SFLs) are one consumer product that can be recycled. Since fluorescent lamps (FLs) contain significant quantities of a toxic element, mercury, a special technology for disposal is required. The FLs are normally either a 4 or 8-foot long straight tube or a circular tube. The tube diameters are typically 1-inch, 1.5-inches, or 2.125-inches. Every lamp is labeled with a code containing information in the following order: lamp type (e.g. F= fluorescent), lamp length (e.g. 12”, 24”, or 96”) or nominal wattage (e.g. 40w), and shape (e.g. T= tube, B or U= u-shaped, C= circular) (Davis, 2001). The components of FLs are shown in Figure 2.1.



1. Glass
2. Fluorescent Powder
3. Inert gas filling
4. Mercury
5. Anode Ring
6. Electrode + Emitter
7. Lead Wire
8. Stem Glass

Figure 2.1 The components of a fluorescent lamp (Philips Electronic (Thailand) Co. Ltd., 2004)

The amount of mercury in a FL depends upon the type of lamp and the year of manufacture. The mercury content in FLs made prior to 1992 was > 40 mg in T12 lamps (1.5 inch diameter tube) and > 30 mg for T8 lamps (1 inch diameter tube). By 1997, FL manufacturers had reduced this amount to < 21 mg for T12 and < 10 mg for T8, respectively (US.EPA, 1998).

Based upon the study of the Research Triangle Institute, the mercury emitted due to a lamp breakage was found to be 6.8 percent of the total mercury content per lamp (US.EPA, 1998).

Moreover, the National Electric Manufacturers Association (NEMA, 2000) estimated that mercury vapor from non-operating lamps ranged from 0.06 to 0.2 percent of the total mercury content. Additionally, NEMA also estimated that mercury emissions from broken lamps were about 1 percent of the total mercury which was much lower than that reported by the EPA, 1998. Aucott et al., 2003 did a study on the release of mercury from broken fluorescent bulbs. Relying upon an assumption that all mercury released was as an elemental vapor, it was found that between 17 and 40% of the mercury in broken low-mercury fluorescent bulbs was released into the air within a two-week period immediately after the breakage. At high temperatures, the releasing rate increases. Thus, one-third of the total mercury released would occur during the first 8 hours after the breakage.

In relation to health, mercury attacks the central nervous system and adversely affects the mouth, gums, and teeth. High exposure over long periods of time will result in brain damage and ultimately death (OSHA, 2004). In the U.S, the SFLs were classified as a hazardous waste since they exhibit the toxicity characteristics (EPA Hazardous waste number D009). Therefore, they have been fully regulated as a hazardous waste. However, since this regulation is rather stringent, thereafter, the EPA announced changes to the hazardous waste rule, because SFLs are not only discarded by industries but also by households. Therefore, to classify this kind of waste as industrial hazardous waste may not be appropriate or adequate. Thus, these changes resulted in classifying the SFLs as a universal waste. A universal waste is considered a low risk hazardous waste generated by a variety of people. This waste has three categories: CRTs, thermostats, batteries and lamps (fluorescent tubes, discharge lamps, mercury vapor lamps, batteries (not auto), and mercury thermostats). Needless to say, this waste must be disposed of properly (US EPA, 1998).

In Thailand, fluorescent light tubes are still classified as hazardous materials under the Notification of the Ministry of Industry No.6, B.E.2540 (MOI, 2002). A study of the Pollution Control Department (PCD, 2004) indicated that the quantity of SFLs discarded in Thailand is approximately forty-five million lamps per year. The study also suggested that the demand for fluorescent lamps has been growing due to the population and economic growths.

2.2 The situations of spent fluorescent lamps disposal in Thailand.

As mentioned in the previous section, SFLs can cause potential adverse impacts on human health, the ecosystem and environment, especially when the systems of collection, handling, storage, and disposal are improperly managed. In the past, generated SFLs in Thailand were not discarded systematically. These could've resulted in mercury exposure to the environment when the lamps were broken and in the end, may have induced potential harm and environmental risks. As a result, the PCD have tried to campaign all stakeholders to dispose of these SFLs systematically. The PCD has set out a voluntary and systematic disposal program providing safe collection and disposal systems. The program has been successfully accomplished. However, SFLs disposal problems in Thailand still occur since existing recycling and non-recycling technologies for a safe disposal of SFLs has belonged exclusively to private sectors. The PCD has presently limited technological capabilities in establishing safe disposal systems.

In 2004, the PCD had conducted a pilot scale project regarding the recycling of SFLs in Thailand. The feasibility of various alternatives for the disposal of fluorescent lamps was examined (CoCusi Coque (Thailand) Co., Ltd., 2004). The results of the study indicated that recycling is still superior to other alternatives for SFLs disposal. However, the PCD study can help the decision maker only to find out the comparative between each alternative. The study did not suggest what they must do with these generated lamps in terms of environmental aspects, life cycle assessment, or economic aspects. A review of the literature reveals that the state-of the art technology, a safe disposal of SFLs, is in the stage of research and the commercial will be mentioned in next section.

2.3 Disposal technology to dispose of SFLs

There are a number of studies concerning the safety of SFLs disposal including both recycling and non-recycling processes. Rabah et. al., 2003, did a study on the aluminum and nickel-copper alloy recovery from SFLs. Water containing 35% acetone was used to capture the mercury vapor while the spent lamps were de-capped. Krivanek, 1996, reviewed three mercury control technologies: activated carbon injection, sodium sulfide injection, and wet scrubbing for municipal waste combustors (MWCs). It was concluded that these technologies suffered from disadvantages or potential deficiencies since an amount of mercury released from the combustor was still taking place after using these mercury control technologies. Poonphunchai, 1996, studied the stabilization of heavy metal sludge containing chromium, mercury, and iron of industrial wastewater, by adding sodium sulfide before solidifying the waste with ordinary Portland cement and lignite fly ash. The results indicated that the stabilization efficiency of mercury were about 91.40% and 99.40% when using sodium sulfide at 1.75 and 3.00 times the stoichiometric amount, respectively, with a waste/binder ratio of 0.25. Padungkettiwong, 1997, investigated the stabilization of heavy metal from FL residue by adding sodium sulfide before stabilization. The results showed that the optimum ratio of sodium sulfide for mercury stabilization was 1.75 times the stoichiometric amount with a stabilizing efficiency of about 97.72% and 97.77% using cement mixed with silica fume and cement mixed with lignite fly ash as binders, respectively. Intrchom, 2005, developed a model of the SFL crushing unit, focusing on mercury vapor minimization. The emission of mercury vapor from the crushed SFLs was studied. The study also evaluated the efficiency of crushing a unit in terms of reducing the amount of emitted mercury vapor and leaching of mercury from FL residue.

However, commercially, the existing technologies for the disposal of SFLs can be classified into two categories, the first is recycling and the second is non-recycling. A simplified diagram of the existing technology for SFL recycling is shown in Figure 2.2. From this figure, an explanation for each processing step is provided as follows:

The Cut and Blow Step: Starting at the point where SFLs are fed into the recycling process, the metal caps and other components at the ends of the lamps will be cut and separated from the lamps. Then, the residues in the stem glass, such as fluorescent powder and mercury vapor, will be blown out. After that, these residues will be sent through a phosphor purification and mercury distillation process for phosphor and mercury recovery, respectively. The stem glass will be sent through a tube crushing process, while the metal caps are sent through a sorting process.

The tube crushing process: In this process, the stem glass released from the cut and blow step will be crushed as cullet. This cullet will be transported to a glass tube manufacturing plant and used as raw material to produce new glass tubes.

Metal Caps Sorting: In this step, aluminum and other materials, such as plastic, will be separated.

Phosphor Purification and Mercury Distillation: Phosphor and Mercury, which are emitted during the cut and blow process, will be purified in this process. Thus, the end products are pure phosphor and mercury.

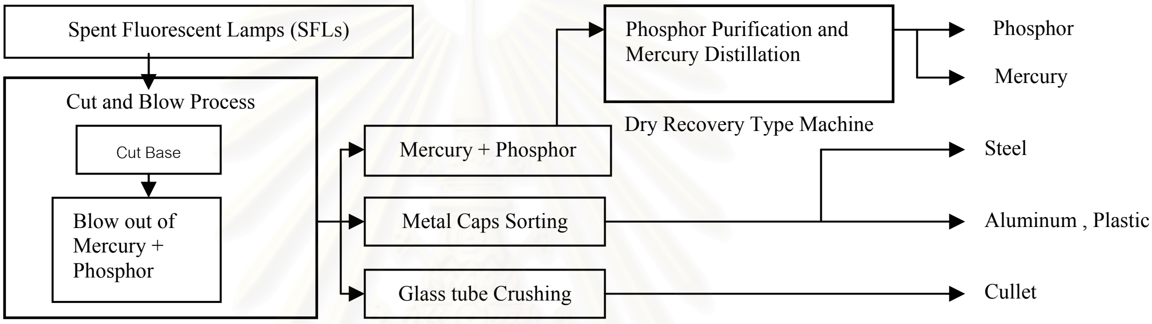


Figure 2.2 Existing technology for the SFL recycling process in Japan
(CoCusi Coque (Thailand) Co., Ltd., 2004)

Currently, the SFL recycling in Thailand is carried out only for cullet recovery. Other components are sent to secure landfills. Therefore, the decision-making model that was developed in this study is only suitable for the current situation. A simplified explanation of the current operating condition is shown in Figure 2.3.

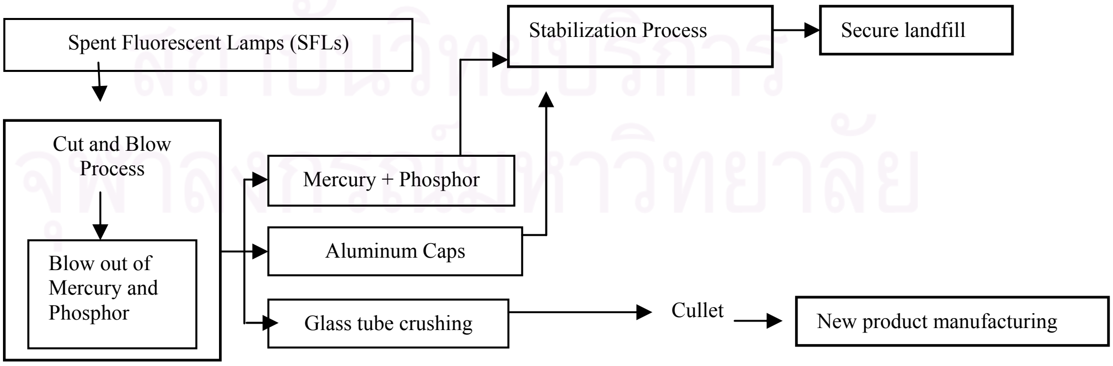


Figure 2.3 Existing technology for the SFL recycling process in Thailand
(Philips, 2004)

From Figure 2.3, after SFLs are passed through the cut and blow step, its outputs are divided into three parts. The first and second parts, mercury + phosphor and aluminum caps will be sent through a stabilization process and to secure landfills, respectively. The third part, glass tubes, will be sent through a tube crushing process and recovered as cullet. Finally, the cullet will be used as a raw material (recovery material) for the manufacturing of new products (glass tube production).

In the second category, non- recycling,, the existing technology for SFL disposal is shown in Figure 2.4. Its explanation is provided as follows:

The crushing stage: SFLs will be fragmented by a crusher in this stage.

The stabilization and solidification stage: After the SFLs are crushed, the material will be sent to be mixed with sodium sulfide and cement in a mixing container for stabilization and solidification, respectively. Then, the mixture will be put into 200-liter containers and retained for 3-5 days for settlement into a solid. During the process, samples will be taken for testing if the amount mercury leached is over the standard value. If so, then, the material will be sent back through the stabilization process. On the contrary, if the results comply with the standard value, the stabilized material will be sent to a secure landfill.

The secure landfill stage: In this stage, solidified material is sent to a secure landfill.

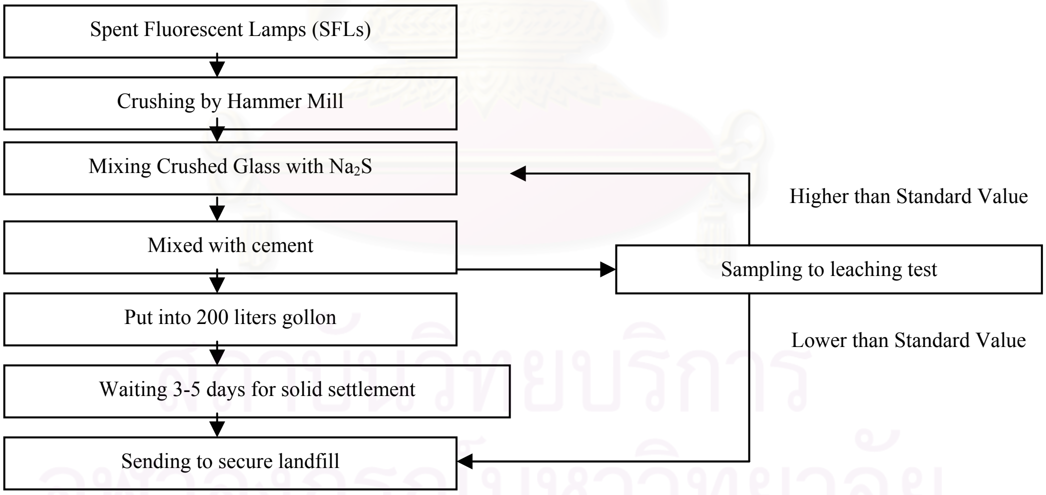


Figure 2.4 Existing technology for the SFL disposal process by non-recycling (CoCusi Coque (Thailand) Co., Ltd., 2004).

2.4 Life cycle assessment methodology theory

The Life Cycle Assessment (LCA) is an environmental management tool that enables quantification of environmental burdens and their potential impacts over the whole life cycle of a product, including impacts that arise from activities encompassing extraction and refining of raw materials, transportation, production, use and waste disposal of a product or of a process. The methodological framework of the LCA comprises the following four phases (ISO, 1997)**:**

1. Goal and scope definition: selecting the system boundaries (see Figure 2.5) to ensure that no relevant parts of the system are omitted;
2. Inventory analysis: performing mass and energy balances to quantify all of the material and energy inputs, wastes and emissions from the system, i.e. the environmental burdens;
3. Impact assessment: aggregating the environmental burdens quantified in the inventory analysis into a limited set of recognized environmental impact categories, such as global warming, acidification, ozone depletion, etc.;
4. Interpretation: using the results to reduce the environmental impacts associated with the product or process.

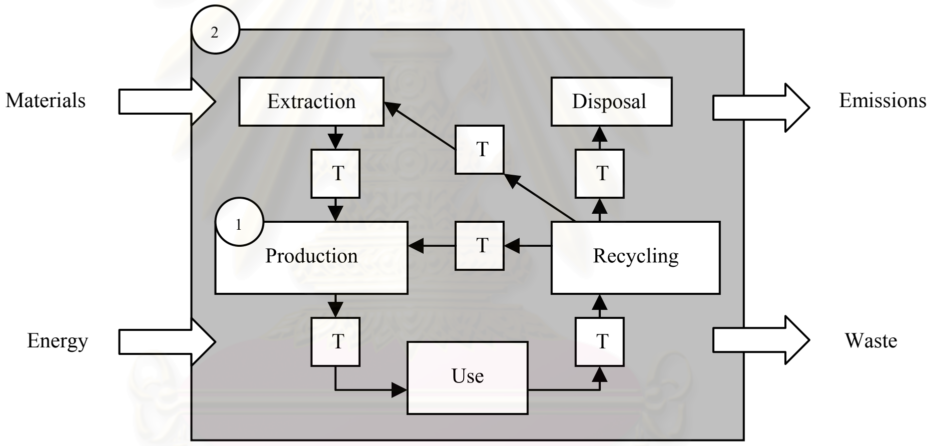


Figure 2.5 Stages in the life cycle of a product (system boundary: 1, process analysis; 2, life cycle assessment; T, transport.)

However, in the impact assessment stage, the methods used to assess the amount of environmental impact vary due to the distinct kinds of concerns which require different approaches. The Environmental Design of Industrial Products method (UMIP, in Danish), will show sixteen categories of impacts, while the Eco-indicator 99 method, individualist version, is only concerned with ten categories of impacts. In this study, the method selected was the Eco-indicator 99 method, individualist version. Therefore, in this section, an assessment of environmental impacts by the Eco-indicator 99 method was also reviewed. Using this method, the impacts were classified into three main groups. The first group concerning human health (unit: DALY= Disability adjusted life years; this means different disabilities caused by diseases are weighed), was composed of carcinogens, respiratory organics, respiratory inorganics, climate change, radiation and ozone layer. The second group concerning the ecosystem quality (unit: PDF*m^2yr; PDF= Potentially Disappeared Fraction of plant species) was composed of ecotoxicity, acidification/eutrophication and land use. The last one concerning resource depletion (unit: MJ surplus energy: additional energy requirement to extract a kg of a mineral in the future) was focused on minerals. To relate the method to this study, the amount of environmental impacts in the life cycle of SFLs generated by different alternatives of SFL disposal were examined. In corresponding with the LCA principle, the most important activities conducted to assess environmental impacts were calculated according to the following procedure..

There are several activities in a recycling process chain. Initially, the SFLs were transported from generation nodes (source nodes) to recycling plants. One material consumed in this process chain is fuel. At the same time, pollutants emitted from transportation vehicles used in these activities were also taken into account. So, environmental impacts caused by these processes are due to the consumption of fuel and the emission of pollutants from transportation. The various kinds of environmental impacts induced in this process are dependent on the amount of weight and distance of transportation. Also, environmental impacts occurred during production of material and energy used in the SFL disposal process including the emission of pollutants and residue waste from the recycling process. The environmental impact from the production of material and energy used in the ultimate disposal of residue waste generated from the disassembly process including that which was caused by the emission of pollutants were taken into account. For the non-recycling process, the environmental impact caused by transportation, production of material, and energy used in the SFL disposal process including the emission of pollutants were taken into account. This even included those impacts caused by the production of new raw material in place of the recovery material that was lost in the system. In conclusion, the ten kinds of environmental impacts generated by the SFL disposal are shown in Figure 2.6.

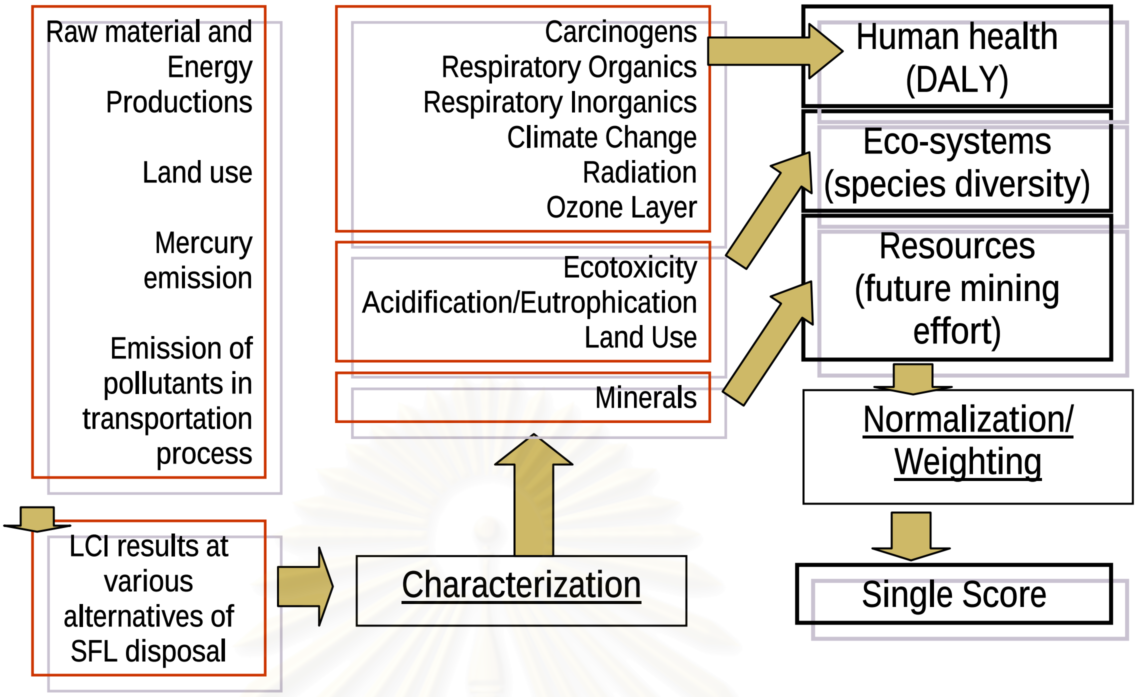


Figure 2.6 Diagram for the assessment of environmental impacts by the Eco-indicator method.

2.5 Reviews of related work for the waste management model.

Modeling of waste management is not a new idea. A comprehensive summary of the models developed in the 1970s, 1980s and early 1990s is provided by many researchers (Morrissey A.J., Browne J., 2004). These authors indicate the changes that have happened in the area of municipal waste management modeling over that time. The first solid waste management models were optimization models and dealt with specific aspects of the problem (Berger, Savard et al., 1999) and (Tanskanen 2000), addressing for example vehicle routing (Truitt et al., 1969), or transfer station siting (Esmaili, 1972). These models suffer from several shortcomings such as having only one time period, recyclables rarely being taken into account, having only one processing option of each type, or having a single generation source (Berger et al., 1999). They were also limited for long-term planning (Sudhir et al., 1996). Much of the work done in the 1970s dealt with applying and refining various optimization and heuristic techniques to provide a more realistic representation of solid waste management practices. The models developed during the 1980s extended the system boundaries of the earlier models. However, the concepts of sustainable waste management or integrated waste management were not terms that were used in any waste management model up to that time. During the 1990s, recycling and other waste management methods were employed in most models developed for planning of municipal solid waste management. The examples of models developed in this period of time included features such as a fixed charge mixed integer programming model. It views a regional waste management system as network flows by using a mathematical formulation for the long range planning of locations and expansion of facilities for regional waste management (Gottinger, 1991). Another example includes the development of a simulation-optimization model to obtain the optimal allocation of trucks for MSW management by reducing traveling and waiting time costs in which this simulation model estimates the waiting time of trucks (Bhat, 1996). Additionally, the multi-criteria model evaluated six waste disposal options in a two dimensional matrix. Assessing data for this model was conducted in two ways: numerical or cardinal valuation when numerical data are present, and an ordinal ranking method when data is absent or unreliable (Powell, 1996). There was also use of the application of a mixed integer linear program (MILP) in the optimization study with dynamic, multi-period model formulation for facility location, timing, and sizing of Barlishen and Batez in 1996 and application of the MIP model with the framework of dynamic optimization considering economic and environmental factors (Chang et al., 1996). Still, there was the development of a period nonlinear programming model (MWS) to analyze SWM systems for a single time period with optimization of the system for a defined objective function in which the objective is to minimize the total cost of MSW management systems. Environmental considerations are addressed through integrating emission constraints and fees (Ljunggren and Sundberg, 1997). Also there was the development of a multiple attribute decision system (MADS) model that is a simulation-planning model composed of two modules (screening and evaluation) in which the screening module assists in selecting feasible MSW management alternatives based on constraints set by decision makers while the evaluation module builds on the previous module and environmental impacts of MSW management and policy. This last model accounts for environmental transportation costs only in terms of vehicle emissions (Rubenstien, 1997). Building upon the LCA technique developed in 1997 by ISO that has taken a role in assessing environmental impacts in industrial chemical processes, it is also necessary to consider all of processes involved from the “cradle to grave” (LCA concept) in order to assess the environmental effects that happen as a result of a waste management system. These are the reasons that since 1997, most of the waste management models are being developed by considering the LCA concept. It is the suggested methodology for the integrated analysis of cost and environmental impacts by linking two modeling approaches for strategic ISWM planning: the MIMES/waste model and the LCA model of Sundberg and Ljunggren in 1997.

The LCA is a technique that has been applied in waste management modeling to help decision makers find out the best waste management option since it provides minimum environmental impact from the life cycle of product. However, its use is not sufficient to advise decision makers on what they must do with their waste.

In conclusion, the LCA can be used to assess the environmental impacts that have occurred in all life cycles for each kind of product. It can not be used to find out the optimum way to manage the product at the end of its life. However, the decision making model is a model that decision makers can set up with decision variables in desired constraints and objectives. However, an economic criterion was a point that decision-makers must still be considering. For these reasons most optimization models or decision making models developed for waste management attempt to incorporate economic criteria considerations. In terms of the LCA, it takes in economic considerations in the models such as in the study of Daskalopoulos et al., 1998 which shows that environmental costs are those associated with emissions of greenhouse gases and expressed in terms of equivalent global warming potential (GWP). An integer LP model was developed as a strategic design approach for optimization of a regional hazardous waste management system in which the objective was to minimize total costs and risks (Nema and Modak, 1998). Azapagic, A. and Clift, R. 1999 presented the optimum LCA performance (OLCAP) methodology. This study introduced the use of multi-objective system optimization in the LCA as a tool for identifying and evaluating the best possible options for environmental management of a product system. Warren Mellor et al., 2002, studied a mathematical model and decision-support framework for material recovery, recycling and cascade use which focused on industrial ecology and logistics support. Minciardi, R., Paolucci, M., Robba, M., and Sacile, R. 2003, studied a multi-objective approach for solid waste management by formulation of a decision model that they applied to the management of municipal solid waste. Four main objectives were proposed, reflecting the most important and conflicting aspects of decisions, specifically: minimizing economical costs, incinerator emissions, the filling time of the sanitary landfill and maximizing material recovery. Abou Najm, M. and El-Fadel, M., 2004, developed a computer-based interface for an integrated solid waste management optimization model. This model can be applied to use in one time period and only the cost and benefits were taken into account.

2.6 The key dimensions for differentiating between available researches

Morrissey, A.J. and Browne, J. 2004 reviewed current waste management models. They showed that most can be categorized into three categories, based on cost-benefit analysis, life cycle analysis, as well as the use of a multi-criteria technique: AHP.

<u>Models based on a cost benefit analysis:</u>

This tool enables decision-makers to assess the positive and negative effects under a set of scenarios. This approach converts all impacts into a common measurement. The measurement is usually in monetary value. This means that impacts, which do not have a monetary value, such as environmental impacts, must be estimated. There are several ways to do this, such as estimating the costs of prevention and control to avoid a negative effect (e.g. the cost of pollution control on an incinerator) or willingness to pay for environmental improvements. Social impacts can also be evaluated in a similar manner, although social impacts were not included in any of the waste management plans. On completion of the analysis, the scenario with the greatest benefits and least costs is the preferred scenario.

Benefits and limitations: The results of the analysis are presented in a precise or quantified manner. Impacts are measured by summing up each impact into one monetary figure. It enables decision-makers to see what scenarios are efficient for their resource uses. There is uncertainty in estimating the monetary value of several environmental and/or social impacts in monetary terms. This also raises ethical issues. The assumptions on prices may change during the lifetime of the waste program, resulting in a change in a preferred outcome (e.g. changes in landfill costs may have an impact on how much waste is recycled)

<u>Models based on life cycle analysis</u>

Life cycle assessment is a tool that studies the environmental aspects and potential impacts throughout a product’s life from raw material acquisition through production, use and final disposal (i.e. from “cradle to grave”) (ISO 14040, 1997). While most life cycle studies have been comparative assessments of substitutable products delivering similar functions (e.g. glass versus plastic for beverage containers), there has been a recent trend towards the use of life cycle approaches in comparing alternative production processes. This includes the use of the LCA in comparing waste management strategies (Berkhout and Howes, 1997). It also provides a general overview of the product system, which can then be combined with other assessment tools, such as risk assessment to evaluate the product or service over the entire life cycle. According to McDougall et al., 2001, the LCA offers a system map, that sets the stage for a holistic approach and then by comparing such system maps for different options, whether for different products or waste management systems, environmental improvements can be made. If a holistic approach such as the LCA is not applied, concentrating on individual issues, such as euthrophication, may worsen the system as a whole with respect to other environmental issues. McDougall et al., 2001, linked the concepts of Integrated Waste Management with that of Life Cycle Analysis. Integrated Waste Management systems combine waste streams, waste collection, and treatment and disposal methods with the objective of achieving environmental benefits, economic optimization and social acceptability. The model developed by McDougall et al., 2001, called the IWM-2 is based on both the IWM and LCA concepts. The technique of the Life Cycle Assessment consists of four phases each of which is subject to International Standards: (ISO 14041, 1998; ISO 14042, 2000; ISO14043, 2000) for guidelines in their use.

Under benefits and limitations, the use of LCA techniques will not necessarily guarantee that one can choose which option is ‘‘environmentally superior’’ because it is not able to assess the actual environmental effects of the product, package or service system. The actual environmental effects of emissions and wastes will depend on when, where and how they are released into the environment. Other tools, such as risk assessment, are able to predict the actual environmental effects, but these techniques do not cover all environmental issues in the life cycle. The LCA allows the trade-offs associated with each option to be assessed and comparisons made. The LCA is but one tool in the ‘‘environmental management toolbox,’’ and should not be used in isolation to decide such issues as which waste management treatment option is to be preferred, (EUROPEN, 1996; Finnveden and Ekvall, 1998). A difficulty associated with the LCA is establishing where the boundary is and what the definition of the functional unit is (Ekvall, 1999). The results produced by variations of LCAs (e.g. investigating the same product) differ in practice (EEA, 2003). LCAs are restricted to looking at environmental impacts only, although both Harrison's et al. (2001) and Craighill and Powell's (1996) models extend the life cycle assessment methodology to incorporate an economic evaluation of the environmental impacts.

Models based on multi-criteria decision analysis.

A brief history of the origins of multi-criteria evaluation methods is given by Bana E Costa et al., 1997. Despite an early insight by Benjamin Franklin into multi-criteria formulation of decision models in 1772, when Franklin used structuring and evaluation to solve problems with conflicting criteria and uncertainty, it was not until 1972 that the term multiple criteria decision making (MCDM) was introduced into management science in the United States. In Europe the terms multi-criteria decision analysis (MCDA) are more common for the same reason. Over the past two decades, MCDA has developed into a discipline in its own right. A common characteristic of all MCDA approaches is that taking several individual and often conflicting criteria into account in a multidimensional way leads to more robust decision making rather than optimizing a single dimensional objective function (such as cost benefit analysis). In addition, the multi-criteria approach assists decision makers in learning about a problem and the alternative courses of action from several points of view. The normal approach is to identify several alternatives, (such as different waste management scenarios) which are then evaluated in terms of criteria that are important for the model or circumstances of the model being developed. The result is a ranking of the alternatives. The type of criteria chosen in these model types depends on the objectives of the model, and therefore, could include risk assessment or environmental impact assessment. A detailed description of the various MCDA techniques can be found in Keeney and Raiffa, 1976 (MAUT), Roy, 1991 (ELECTRE), Brans et al., 1998 (PROMETHEE), Saaty, 1980 (AHP), Jacquet-Lagreze and Siskos, 1982 (UTA) and Zeleny, 1982 (Multiobjective Optimisation). Further details on comparing, the main MCDA techniques can be found in Guitouni.

2.7 Other related work for the LCA and decision making model for waste management in Thailand.

The LCA in Thailand

Rodprasert N., 2005, studied the environmental impact evaluation of fluorescent lamps using a life cycle assessment. The life cycle assessment (LCA) was implemented to compare the environmental impacts along the life cycle stages of two

18-watt FLs, the standard and super model. By using the Environmental Design of Industrial Products (EDIP) in the assessment, the results indicated that the impacts to such categories were induced during the utilization stage. Human toxicity which was induced by air pollutants during the utilization stage from the standard model and then the super model were similar, 93.13% and 92.15%, respectively.

A decision making model for waste management

In at least one case study in Thailand, there was application of a decision making model with waste management. This case study, a capacity expansion model exploring the trade off between economies of scale and the time-cost of early construction of wastewater treatment plants, was developed for a 224-km. stretch of the Chao Phraya River in Thailand. The model was designed to find the cheapest waste water treatment. The capacity expansion path included treatment plant sites, capacity increments, and associated BOD removal efficiencies to meet ambient water quality standards throughout every period over the planning horizon (Koetsinchai, 2001).

2.8 Basic Concepts of a decision-making model

In this study, the LCA technique was applied to assess environmental impacts that result from significant activities in the life cycle chain of FLs influenced by the recycling of SFLs. Moreover, an optimization technique was also applied to find out the best alternative for the recycling of SFLs to achieve a minimal environmental impact subject to recycling cost constraints. The theoretical background of optimization used in this research is reviewed as follows:

Statement of an optimization problem:

An optimization or a mathematical programming problem can be stated as follows:

$$\text{Find } X = \{x_1, x_2, \ldots, x_n\} \text{ which minimizes } f(X)$$

Subject to the constraints of:

$$g_j(X) \leq 0, \quad j = 1,2,\ldots,m$$

$$l_j(X) = 0, \quad j = 1,2,\ldots,p$$

where X is an n-dimensional vector called the *design vector*, f (X) is termed the *objective function,* and g_j (X) and l_j (X) are known as *inequality* and *equality* constraints, respectively.

The number of variables n and the number of constraints m and/or p need not be related in any way. The problem stated in equation (1) is called a *constrained optimization problem.* Some problems do not involve any constraints and can be stated as:

Find X = $\{x_1, x_2, \ldots, x_n\}$ which minimize f (X).

Such problems are called *unconstrained optimization problems.* At the same time, these optimization problems can be classified as convex or nonconvex problems.

- For convex problems, the equations for optimization are shown in terms of linear or nonlinear properties and the domain boundary will be definite. By using first or secondary equations, both the global value and local value can be determined from these problems.
- For nonconvex problems, the boundary of the domain (the range of decision variables) is not limited; the optimization cannot be carried out by first or secondary equations. Therefore, these problems are very complicated in the effort to find out the optimum value of decision variables.

2.9 A review of solution algorithms

Innovations in optimization techniques were stimulated by efforts to solve practical problems during World War II (1940s) and by the later rapid evolution of computer technology. All the techniques typically involved mathematical problem formulation and solution procedures aimed at optimization subject to a number of constraints. “Linear programming (LP)”, developed by Dantzig in 1947, was the technique used to solve an early version of water quality management problems. It was developed for problems whose objective functions and constraints were linear or could be so approximated. Although LP was developed in 1947, the approach was not applied to any practical situation until Koopmans (1951) used the technique in an activity analysis of production and allocation.

"Nonlinear programming" (NLP) was developed simultaneously with the increasing interest in LP. In 1950, Kuhn and Tucker created a pioneering theory of nonlinear programming which dealt with the necessary and sufficient conditions for finding an optimal solution to programming problems. This was the foundation for later NLP techniques. NLP was designed to solve problems in which the relationships among variables in objective functions or constraints included nonlinear terms. Later, several methods of solving NLP were suggested. One solution method, convex separable programming (CVSP), was proposed in 1954 by Charnes and Lemke, who published a paper on solving a minimization problem with a separable objective function. In 1959, Wolfe proposed a method for solving a quadratic programming (QDP) problem.

Interest in integer linear programming problems arose in the mid 1950s. One of the pioneering papers on an integer-programming problem (IP) was published by Dantzig, Fulkerson, and Johnson in 1954. Later, in 1957, Markowitz and Manne suggested a numerical technique for solving nonlinear integer programming.

One of the most important contributors to the development of optimization techniques was Bellman (1957) who developed an algorithm under the rubric of "dynamic programming" (DP). DP is designed to facilitate the solving of a large-scale optimization problem by decomposing it into smaller sub-problems in which choices are made in a series of decision stages (such as expansion time or locations) with varying input states. This process is termed multi-stage analysis, a process designed to reduce the volume of computation. DP has been employed in much traditional research in the CEM (Capacity Expansion Model) to attack problems that involve both choices over time and space in which myopic calculus techniques are not in general, reliable guides.

The original works of Dantzig, Fulkerson and Johnson, and Markowitz and Manne can attack only problems with integer solutions. To address problems related to both integer and continuous variables, Land and Doig (1957) and Beale (1985) developed a branch and bound algorithm (B&B) for solving a mixed-integer programming problem (MIP). There are several types of NLP problems, and conventional methods may not be able to solve all of them. As a result, in 1960, Rosen introduced a general method for improving solutions of NLP problems using a gradient direction search, called a "gradient projection" (GRP) method. This method provided the spark for the development of a more general computational algorithm for solving NLP problems. In the same year, Gomery (1985) developed a systematic computational technique for solving all IP problems. The availability of mixed-integer programming (MIP) algorithms contributed to the development of capacity expansion management research in that capacity expansion problems are often related to both 0-1 variables and to non-integer variables. For example, a decision may be required on whether or not to build additional capacity in a year and, if so, how much to build. Such a problem is characterized as a "fixed charge" problem (this is a fixed charge problem because of the capital cost of capacity expansion), whose model is based upon a discontinuous mixed-integer programming (MIP) framework.

One drawback of the above conventional programming approaches is that they deal only with a single criterion objective problem. Other considerations must enter as constraints. But in a realistic setting there may be multiple goals not reducible to a single (money) dimension. Lee (1972-3) suggested a "goal programming" (GP) method for solving such problems.

In a real situation, an optimization problem may additionally involve uncertainty. For example, in the context of water quality management problems, such factors arise from uncertainty about ecosystem functioning and management policy. Uncertainty is generally the result of a lack of sufficiently accurate information or a full understanding of how a system operates. For this problem setting, coupled with multiple conflicting goals as mentioned earlier (in other words, there are conflicts between the objective and constraints), Zimmerman (1978) introduced fuzzy mathematical programming for solving multi-objective programming (MOP) problems. He attempted to resolve these conflicts by converting a problem into a new model in which a decision variable is the level of fulfillment of constraints, one of which is now the objective function (i.e. primary objective $\leq \lambda$, where λ is a level of fulfillment). Using a number between "0 and 1" to represent the fulfillment, the new objective function is taken to be maximizing the level of the fulfillment (max λ). Thereafter, LP is applied to solve the fuzzy optimization problem.

Advances in computer technology and correspondingly greater challenges due to an increase in problem dimensionality gave rise to a more advanced computational algorithm for solving NLP. One of the greatest contributions was the generalized reduced gradient (GRG) method, developed by Lasdon (1978) which is employed in the current solvers for NLP problems.

Although several mathematical optimization techniques were developed in the 1950s and 1960s, some practical problems were still too complex to be solved by conventional methods. An intuition-based solution algorithm, called “heuristic programming” (HS), was introduced by Gavett (1965) to solve several complex decision problems. A heuristic algorithm is one that efficiently provides a good approximate solution to a given model by invoking intuitively appealing rules of thumb to produce a solution that may be optimal within certain margins. This method is often used when formal techniques are impractical. Bhalla (1970) was the pioneer in applying a heuristic approach to solving regional water quality planning problems.

Two well-known general heuristic search techniques have been utilized in a recent available solver. One is the Tabu Search method developed by Glover (1989, 1997), allowing for a quick search beyond the neighborhood of the current solution; the other is the genetic algorithm introduced by Goldberg (1989). More recent solvers, such as those developed by Microsoft, Frontline System Inc., Crystal Ball, and ILOG-CPEX, use heuristic methods in conjunction with other formal algorithms to find good solutions for nonlinear problems.

Solving large-scale, non-convex problems continues to pose challenges, and in recent decades, there has been continued effort to extend the ability of heuristic methods to find global optima in capacity expansion contexts. Dutta and Young (1996), for instance, created a heuristic procedure for the capacity expansion of package transmission networks. While Lin et al., 1997, suggested a heuristic algorithm for the optimization of water distribution networks. Also, Pezzella and Merelli (2000) suggested a tabu search method for a shop-scheduling problem. Later, Chelouah and Patrick (2000) proposed a heuristic tabu search for solving a general global optimization problem.

However, the decision making models reviewed were found unsuitable for this project due to the specifics of the model parameters and decision variables. For SFLs, which are different from other wastes in terms of the technology to manage them, these other waste management models cannot be properly applied to this waste stream. The literature review has revealed that there have been no studies aimed at the development of a decision-making model for determining the optimal recycling approach for SFLs. Therefore, development of such a model is the target of this study.

CHAPTER III

METHODOLOGY

In this study, a decision-making model was developed by incorporating a life cycle assessment model into the optimal management policy. To achieve this goal, an inventory analysis using the life cycle assessment principle was conducted to create an inventory model. The output of the inventory analysis involved information regarding the amount of materials, energy consumption, released pollutants, as well as the recovery materials. The information obtained was utilized to analyze environmental impacts. Thereafter, the relationships between the input information and associated impacts were created into a general inventory model. After that, cost and benefit data collected from surveying were used to formulate a cost-benefit model and set out as constraints of the study decision-making model. Finally, the study decision-making model was formulated by incorporating the cost-benefit model into the inventory model. All these processes were divided into six phases.

3.1 The inventory analysis (Phase 1)

In the concept of the life cycle assessment principle, the system boundary of the SFL disposal network was defined in the first stage. Thereafter, the inventory analysis was done. Therefore, to achieve this concept, in this first phase, the system boundary and inventory analysis were defined as summarized below:

3.1.1. A material and energy flow diagram of a SFLs disposal process chain (on the basis of available technology) was developed. The flow reflects activities that consume and generate materials and energy. In effect, it was used to analyze input and output inventory for all activities in the scope of the study or linkages of material and energy associated with each activity. In this study, the scope for inventory analysis included the collection processes, transfer stations, and then transportation of SFLs to either a recycling process or a non-recycling process (Figure 3.1).

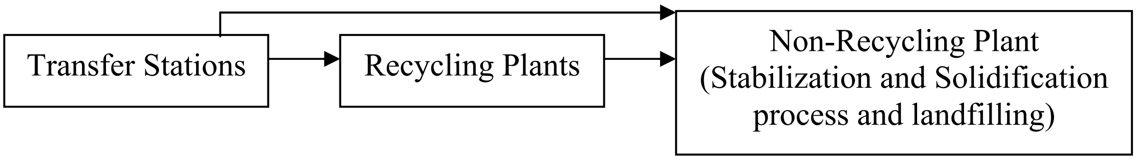


Figure 3.1 The scope of the inventory analysis

3.1.2. The relationships of each inventory were determined and the inventory model formulation of a SFL recycling network was set up. Initially, input and output inventories associated with all activities were examined. Then, emissions of pollutants occurring in material and energy manufacturing were evaluated. Consumption factors and recovery (production) rates were input as parameters for inventory modeling. These input data were collected from actual activities in an existing Thai factory. However, there was some data which was not available from real activities; in such cases, data collected from previous studies was obtained.

For the recycling process, inventory input data was measured. Initially, the amount of SFLs fed to recycling plants was collected manually. The amount of electricity used in each process such as in disassembly, glass tube crushing, and wet scrubber processes, was obtained by reading the electricity gauge meter. The amounts of natural gas and water consumed by the processes were also collected in cubic-meters (m^3). All of these data were recorded once a month. These data were collected for 12 months. The allocation of each input inventory data per a SFL was calculated by dividing the total amount of each input data with the total amount of SFLs fed to the plant in a year. For output inventory data, the amount of cullet was collected by weighing the recovery each month for 12 months or 12 times a year. Because this process was run in a close system, the amount of mercury vapor was sampled from the exhaust air at the stack. Sampling air from the stack was done by using the sampling procedure-active sampler following OSHA's ID-140 method (OSHA, 1991). The samples were taken twice a year. The samples were prepared using OSHA's ID-140 method. Analyzing mercury vapor was done by using a mercury analyzer. After the analysis, the amount of mercury was reported in mg per m^3 of exhaust air. An exhaust air flow rate of m^3 per second was measured using a flow meter. Hence, the amount of mercury vapor released from the process, reported in mg per second, was calculated by multiplying mg per m^3 of exhaust air by the exhaust air flow rate, m^3 per second. Dividing the rate of mercury vapor released, mg per second, by the rate of SFLs fed to the process (SFLs per second), the amount of mercury released from each SFL was obtained in mg per SFL. The amount of mercury in the wastewater from a wet scrubber was measured as follows: First, two samples of wastewater were taken. Then, the samples were prepared and each sample was fed to the mercury analyzer. The amount of mercury in the wastewater which was released into environment per SFL was calculated. The calculation was initialed by multiplying the amount of mercury concentration in mg per m^3 with the amount of water released in m^3 per second (measured by using a flow meter). Then, to obtain the amount of mercury released into the environment per lamp, this amount would be divided by the feed rate of SFLs to the process (SFLs per second). The amount of waste residue was calculated by subtracting the total weight of a SFL with the weight of the cullet and mercury released from the process per SFL. The residue was sent through the stabilization process before landfilling. At the stabilization plant, the amount of residue was measured by weighing. The amount of electricity and water consumption used were also measured by reading from the gauges, respectively. The amounts of sodium sulfide and cement were also weighed. Air was also sampled to determine the amount of mercury vapor released in the same manner as that used in the disassembly process. Due to the existing technology of the stabilization process, there was no wastewater released from the process, since the process was run in a batch. Thus, all inventory data for this stabilization process was collected from the three batches. For the non-recycling process, SFLs were sent through the stabilization process before safely landfilling. Hence, each inventory data was measured in the same manner as performed with the stabilization process in which, SFLs were weighed per batch before feeding through the process. Also, other inventory data such as the amount of cement, sodium sulfide, electricity and water, were collected. Air samples were taken to investigate the amount of mercury vapor, as was performed in the disassembly process. The amount of new glass produced to substitute cullet loss, when SFLs were not sent to be recycled, was accounted for from the amount of cullet generated in the disassembly process. The sources of all data are shown in detail in the following chart, in Table 3.1

Table 3.1 Sources of inventory data.

Activities	Collected Data	
	Measured at site	Literature Review & existing database
Transportations		
Transportations for all activities of concern		♦
All recycling process composed of		
Cut and blow process (disassembly)	♦	
Mercury vapor trapping	♦	
Tube crushing	♦	
Stabilization of residual phosphor powder + mercury	♦	
Landfill of stabilized waste and other residual waste		♦
Non recycling process composed of		
Stabilization process	♦	
Solidification process	♦	
Landfill of solidified waste		♦

After all inventory data were received from this phase, these data were used as input data for environmental impact, cost and benefit assessment modeling in the next phases.

3.2 The environmental impact assessment (Phase 2)

Environmental impacts resulting from resource uses and emitted pollutants in all activities within the boundaries of the problem were assessed. All were done by formulating equations that represented the relationships between each kind of environmental impact and inventory data of all activities, including the preparation of the parameter values in the equation. In this phase, the amounts of the environmental impacts were assessed by the Eco-indicator 99 (I) V2.1 method. In which, the impacts were classified into three main groups. The first group concerning human health (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighed), was composed of carcinogens, respiratory organics, respiratory inorganics, climate change, radiation and ozone layer. The second group concerning the ecosystem quality (unit: PDF*m^{2}yr; PDF= Potentially Disappeared Fraction of plant species) was composed of ecotoxicity, acidification/eutrophication and land use.

The last one concerning resource depletion (unit: MJ surplus energy: Additional energy requirement to extract a kg of a mineral in the future) focused on minerals.

In the first step of this environmental impact assessment modeling, the inventory results obtained from first phase were divided into ten kinds of environmental impacts by multiplying the amount of each inventory with the characterization factors. Then, these output results of ten kinds of environmental impacta were passed through the damage assessment, normalization and weighing processes, respectively. After all of these processes were completed as in the previous presentation, the amount of environmental impact was calculated in a single score unit. In this study, the characterization, damage assessment, normalization and weight factors (which were the model input parameters) were referred to as the secondary data from the database in the Simapro demo version 6.

3.3 The cost and benefit assessment (Phase 3)

The data of costs and benefits was assessed (the costs were determined from the disposal of SFLs by recycling and non-recycling and the benefits by the income generated from selling recovered material resulting from the SFLs recycling process). In this phase, the cost and benefit model for SFLs management was developed. The total cost for SFL disposal management was covered including both costs resulting from the recycling of SFLs and costs resulting from the disposal of SFLs (non-recycling). In the recycling process, the cost was taken into account beginning with the SFLs transportation, disassembly process (at recycling plants), transportation of output material from recycling plants to FL component part manufacturing and ending with the cost for the disposal of residual waste from recycling plants. The cost for SFLs disposal by a non-recycling process depended on the market price of the disposal of SFLs in the non-recycling process. Benefits taken into account included income from selling recovered materials and the revenue obtained by the SFL disposal fee. The SFL disposal fee was paid by SFL generators to manage the generated SFLs.

3.4 A decision making model formulation and design of the computer interface program for optimization (Phase 4)

By linking all models or all equations as presented above together with decision variables, the decision making model for SFLs recycling was developed in this step. The model formulation consists of an objective function and budget constraints presented as follows:

- The Objective function of this model was to minimize the value of environmental impact (in terms of a single score) from the recycling of SFLs.

Environmental impacts were evaluated using the environmental impact assessment principle in the life cycle of a product (ISO 14024, 2000) in which multiple kinds of environmental impacts were calculated in terms of a single score unit (point) by using the Eco-indicator 99 (I) V2.1 method.

- Constraints of this decision making model were the SFLs waste management budget and the net present value of benefit (revenue from selling recovery material and revenue from SFL disposal fee) which must be more than the cost.

- Decision variables of this model are the rate (percent) of recycling, capacity of each recycling plant, and locations for the expanded recycling plants.

The rate (or percent) of recycling was calculated from the decision variables as shown in Figure 3.2. The calculation was shown in equation 3.1.

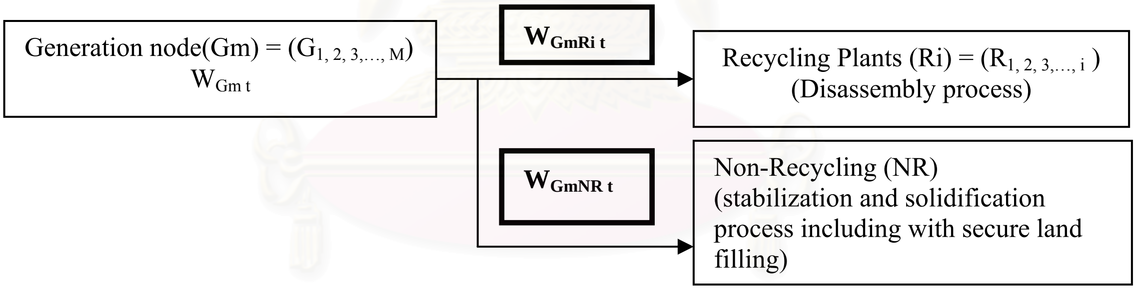


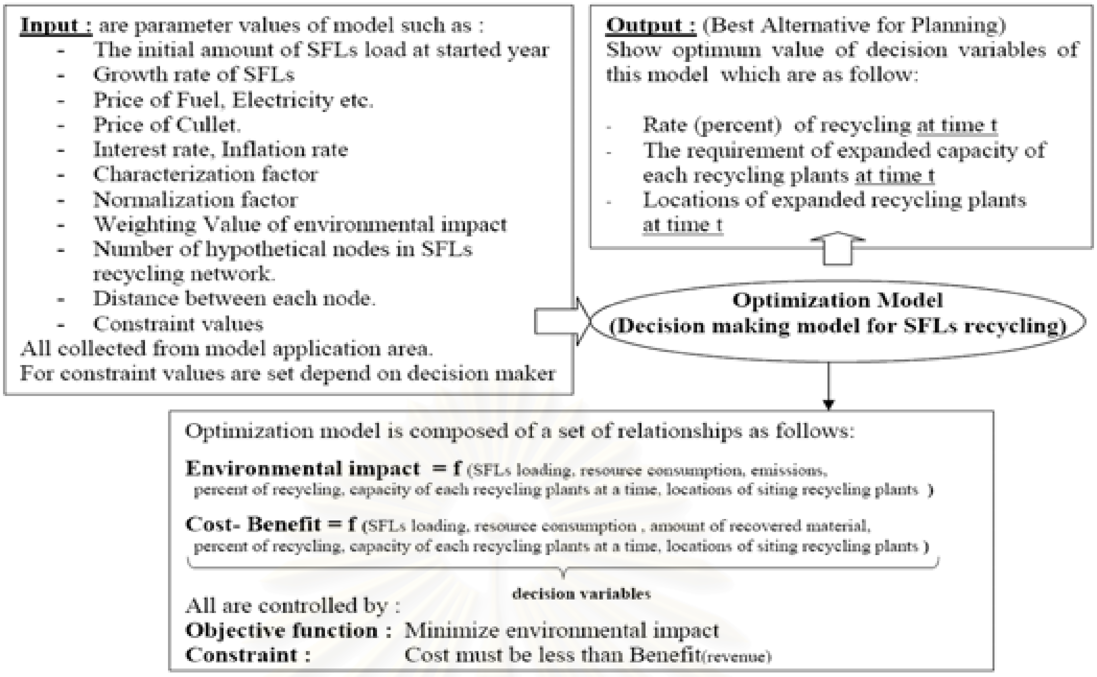
Figure 3.2 Flow diagram of the amount of SFLs decided to disposal.

$W_{Gm\,t}$ = The amount of SFLs generated from generation node m, Gm, at time t
$W_{GmRi\,t}$= The amount of SFLs decided to transport from generation node m, Gm, to recycling plant i, R_i, at time t.
$W_{GmNR\,t}$= The amount of SFLs decided to transport from generation node m, Gm, to non-recycling plant, NR, at time t.

P_t, rate (percent) of recycling at time t

$$= [\sum W_{GmRi\,t} / \sum \underbrace{(W_{GmRi\,t} + W_{GmNR\,t})]}_{\sum W_{Gm\,t}} \times 100\% \qquad (3.1)$$

- Format of this decision-making model is shown as Figure 3.3



Input : are parameter values of model such as :

- The initial amount of SFLs load at started year
- Growth rate of SFLs
- Price of Fuel, Electricity etc.
- Price of Cullet.
- Interest rate, Inflation rate
- Characterization factor
- Normalization factor
- Weighting Value of environmental impact
- Number of hypothetical nodes in SFLs recycling network.
- Distance between each node.
- Constraint values

All collected from model application area.
For constraint values are set depend on decision maker

Output : (Best Alternative for Planning)
Show optimum value of decision variables of this model which are as follow:

- Rate (percent) of recycling at time t
- The requirement of expanded capacity of each recycling plants at time t
- Locations of expanded recycling plants at time t

Optimization Model
(Decision making model for SFLs recycling)

Optimization model is composed of a set of relationships as follows:

$$\underbrace{\begin{array}{l}\textbf{Environmental impact} = \textbf{f}\ \text{(SFLs loading, resource consumption, emissions, percent of recycling, capacity of each recycling plants at a time, locations of siting recycling plants)}\\ \textbf{Cost- Benefit} = \textbf{f}\ \text{(SFLs loading, resource consumption , amount of recovered material, percent of recycling, capacity of each recycling plants at a time, locations of siting recycling plants)}\end{array}}_{\textbf{decision variables}}$$

All are controlled by :
Objective function : Minimize environmental impact
Constraint : Cost must be less than Benefit(revenue)

Figure 3.3 The format of the decision making model for SFL recycling

3.5 Model exploration and testing of model, sensitivity analysis. (Phase 5)

3.5.1. The model input parameter data was collected and prepared, which was specific data for the study area (model application area).

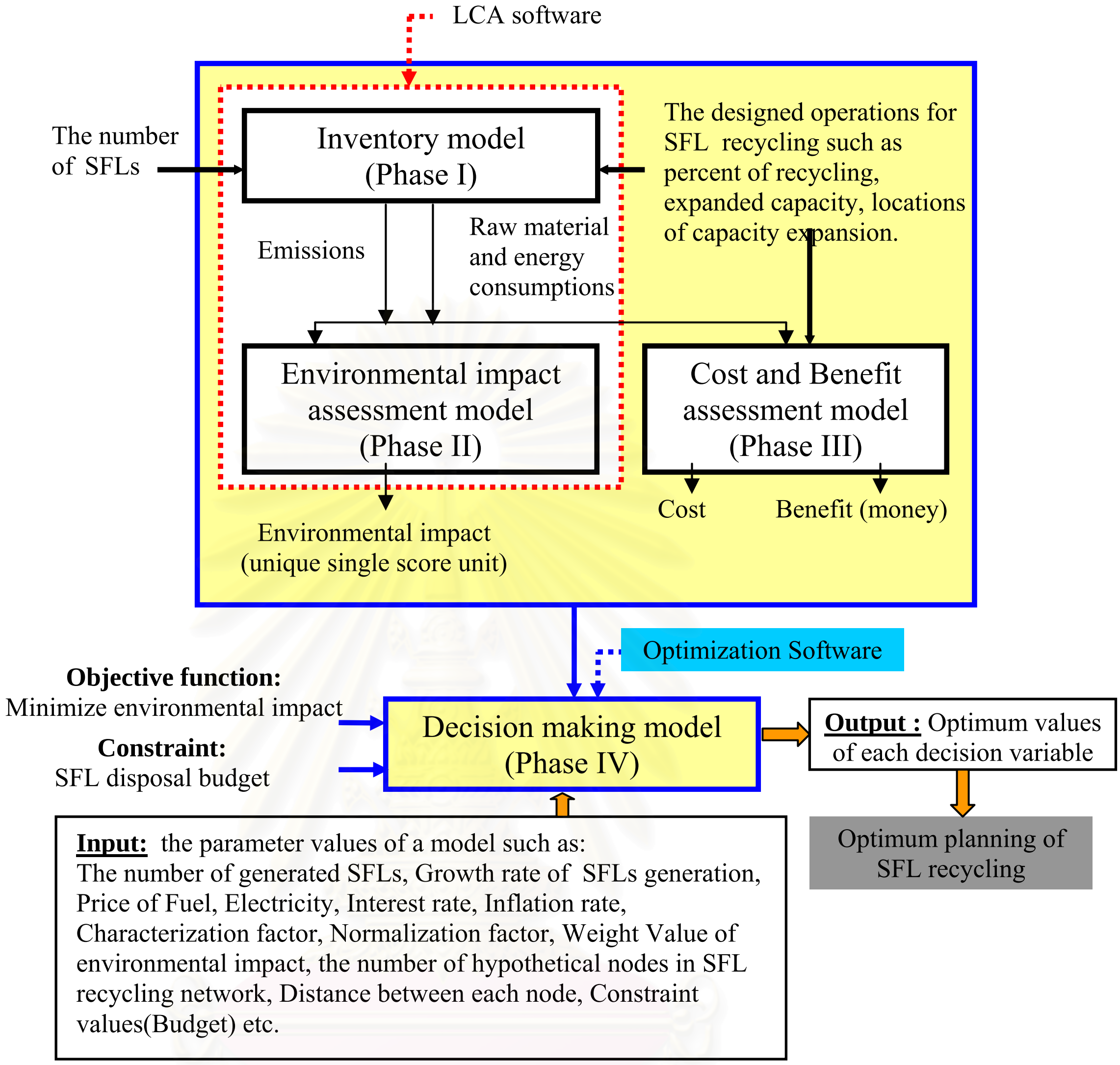
Examples of these area-specific data included rates of SFL generation, the number of hypothetical locations of recycling plants, new product manufacturing plants, as well as, non-recycling plants. They also included the distance between each node, price of cullet, price of fuel and electricity in the study area, the price of SFLs disposal and budget constraint values, etc.

3.5.2. The model was completed with all prepared input values, a test model and sensitivity analysis. Finally, the model determining the optimum planning for the recycling of SFLs in the study area.

3.6 Conclusion (Phase 6)

The solution of the model provided a guideline for SFL recycling planning. It covered such factors as what the optimal recycling percent is, what the optimal capacity to be built is, as well as where the optimum locations for recycling plants are, in order for a policy-maker to set up a national policy for a waste management program for SFLs.

The diagram representing the overall study is depicted in Figure 3.4.



Input: the parameter values of a model such as: The number of generated SFLs, Growth rate of SFLs generation, Price of Fuel, Electricity, Interest rate, Inflation rate, Characterization factor, Normalization factor, Weight Value of environmental impact, the number of hypothetical nodes in SFL recycling network, Distance between each node, Constraint values(Budget) etc.

Figure 3.4 The framework of the study decision-making model

CHAPTER IV

SOCIO-ECONOMIC ASPECTS AND SFL LOADS

In this chapter, socio-economic aspects and the estimation of the loads of SFLs over a 20-year planning horizon were investigated for case study areas in Bangkok and the vicinity. Initially, the backgrounds of the case study areas such as boundaries, locations, sizes and economic growth in the areas were provided. Then, selected locations for each plant in a hypothetical SFL network were obtained. For instance, the locations of hypothetical recycling and the existing non-recycling plants as well as the distance data between plants were collected. Additionally, the amount of SFL loads in the case study areas was estimated on the basis of the amount of generated SFLs within the linearity growth.

4.1 Backgrounds of the case study areas

The case study areas include Bangkok and the vicinity, namely Nonthaburi, Samutprakarn, Samutsakhon, Nakhonpathom, and Pathumthani provinces as shown in Figure 4.1.

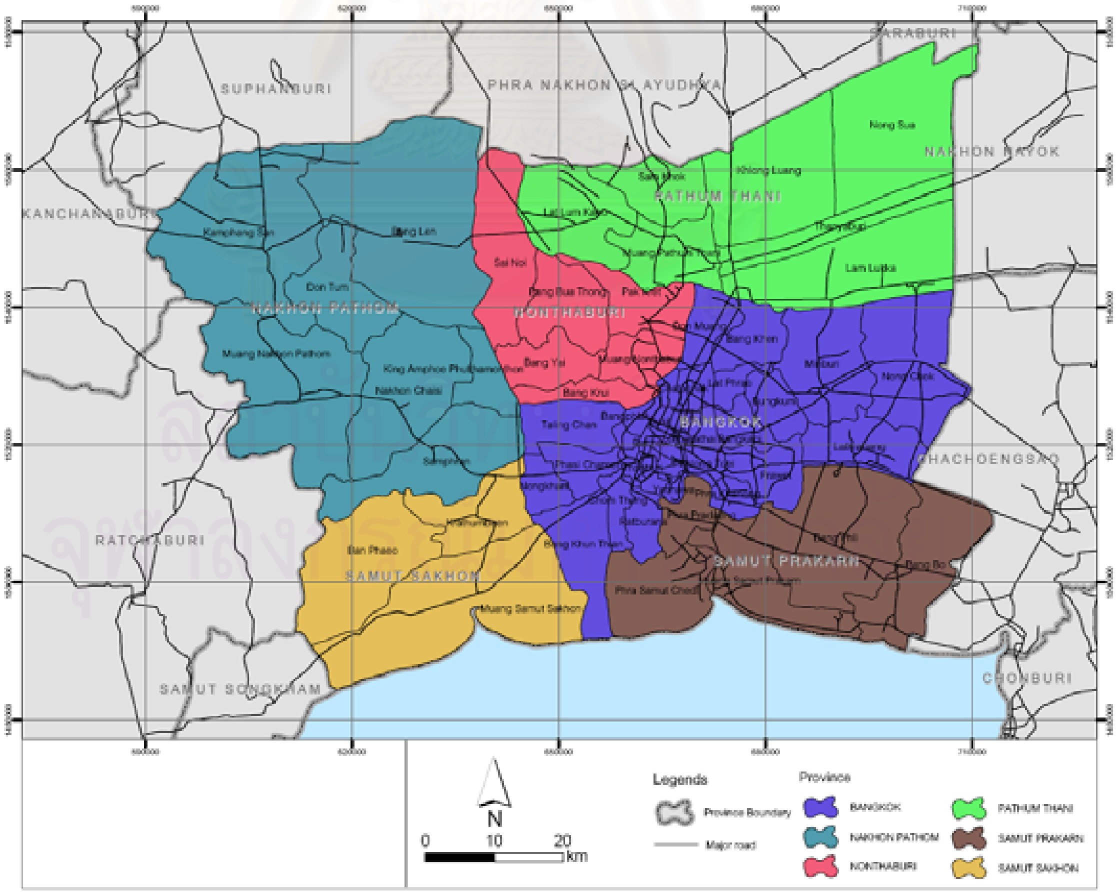


Figure 4.1 Area map of a case study

Boundaries of the case study areas

Bangkok, with a total area of 1,568.737 square kilometers, is the capital city of Thailand. It is located in the central part of the country on the low-flat plain of the Chao Phraya River. Its population is over 7 million by registered record or about 10 million according to daytime population.

Nonthaburi whose total area is approximately 622.303 square kilometers is located in the central part of Thailand. It is 20 km northwest from Bangkok. The northern part of this province is adjacent to Pathumthani and Ayutthaya provinces while the southern part is contiguous to Bangkok. In 2007, its population was nearly 839,029 by registered record.

Samutprakarn with a total area of 1,004.092 square kilometers is located at the end of the Chao Phraya River. The northern border of this province is attached to Bangkok.

Samutsakhon is located in the southern part of central Thailand. It is 30 km southwest from Bangkok. The eastern border of this province is next to Bangkok. The total area of this province is about 872.34 square kilometers.

Nakhonpathom is located in the central part of Thailand. The total area of this province is 2,168.327 square kilometers. It is 56 km northwest from Bangkok. The southeastern part of this province is attached to Bangkok.

Pathumthani is located in the central part of Thailand. The total area of this province is 1,525.865 square kilometers. It is 27.8 km north of Bangkok. The southern border of this province runs parallel to Samutsakhon.

4.2 Economic Growth in the study areas

To predict the amount of SFLs generated in the future, the economic data of the case study areas were required. In this study, the Gross Domestic Products (GDPs) were used as the economic data to predict the amount of SFLs as shown in Table 4.1.

Table 4.1 Gross domestic products in the case study area

Area	**GDP (million bath)**							
	Year							
	1997	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Thailand	**4,732,610**	**4,626,447**	**4,637,079**	**4,922,731**	**5,133,502**	**5,446,043**	**5,930,362**	**6,576,834**
Bangkok and the vicinity	**2,140,692**	**2,009,549**	**2,182,329**	**2,333,318**	**2,451,176**	**2,498,223**	**2,634,069**	**2,898,899**
Bangkok	1,463,761	1,353,479	1,482,516	1,579,297	1,656,113	1,673,941	1,749,548	1,912,622
Nakhonpathom	78,441	71,950	74,231	78,448	81,991	88,866	99,927	108,154
Nonthaburi	72,936	72,163	64,788	65,361	69,012	72,422	76,162	87,682
Pathumthani	143,080	111,775	131,684	130,459	133,865	120,633	133,833	153,960
Samutprakarn	233,681	259,580	300,514	328,021	350,873	370,343	381,261	427,657
Samutsakhon	148,793	140,601	128,595	151,732	159,322	172,018	193,337	208,823

Source: Department of National Statistics (Thailand), 2005.

As shown in Table 4.1, Bangkok has the largest GDP amongst all the provinces in the case study areas, while the province of Nonthaburi has the smallest GDP.

4.3 Locations of Nodes in the SFL network

In this study, locations of each node in the SFL network which were important namely for model runs, included the locations of SFL generating sources, hypothetical recycling plants, the existing non-recycling plants, new product manufacturing plants, a landfill area and other necessary facility locations in the SFL disposal process. In this study, some assumptions relevant to locations were made as stated in the following descriptions.

Locations of the SFL generation sources within the study areas

In this study, it was assumed that all SFLs generated in a province were collected and transported into a particular area in that province. Alternatively, there was one generation source node in each province. Hence, there were a total of six SFL generation sources located within the study areas, namely in Bangkok, Nakhonpathom, Nonthaburi, Pathumthani, Samutprakarn, and Samutsakhon.

Locations of hypothetical recycling plants in the study areas

In selecting the sites for the hypothetical recycling plants, some assumptions and factors were taken into consideration. Firstly, recycling plants had to be located in the areas whose remaining sizes, in the corresponding planning year, were sufficient to respond to additional demand capacities. Secondly, plants had to be located at the place specified by the Thai waste management regulations issued by the central and local government associated with their areas.

As mentioned earlier, the study areas included Bangkok and the vicinity. In these provinces, the possible sites for hypothetical locations of recycling plants were selected on already existing recycling plants because these locations were located in industrial estate areas. In these areas, the environmental impact assessment (EIA) had already been done. Also, these locations had already received the permit from the central and local governments. Therefore, the possible sites for hypothetical locations of recycling plants were located in Samutprakarn province, in the district of Bangpu, and in Pathumthani province, in the district of Bangadhee.

Locations of non-recycling plants

In this study, there were two possibilities for SFL non-recycling. The first was if the total cost of recycling was higher than that of non-recycling. The second was in case that there were residual wastes generated from the disassembly processes of a recycling plant. In such cases, the wastes would be sent through stabilization and solidification processes; and finally, land filling at the same site. In this study, the hypothetical non-recycling plant was designed to be located at an existing plant located in Ratchaburi Province.

The location of a new product manufacturing plant

In this study, reusable waste material obtained from the disassembly process included the cullet. The recycled cullet was sent to the manufacturers of fluorescent glass tubes for production as reused materials. Hence, the nearest existing plant for glass tube manufacturing was located in Samutsakhon Province.

4.4 Distance data

Since the transportation process and associated transport distance affected both the cost and fluorescent emissions in the environment, data on distances between all nodes in the hypothetical network area was necessary to obtain. In these study areas, distances from the SFL generation nodes to recycling plants or to the non-recycling plant, as well as, from the recycling plants to the glass tube manufacturing plant were also collected as shown in Table 4.2. These data were used to estimate contributed costs and environmental impacts arising from the transportation process.

Table 4.2 The data on distances between all nodes in the hypothetical network

Location (Province/Amphur)	**Distance in one way (km)**			**Distance in two way (km)**		
	Ended Point			Ended Point		
	Hypothetical Recycling Plant 1 (Samutprakarn/Bangpu)	Hypothetical Recycling Plant 2 (Pathumthani/ Bangadhee)	Secure landfill Site ,Non-Recycling Process. (Ratchaburi /Muang)	Hypothetical Recycling Plant 1 (Samut prakarn/ Bangpu)	Hypothetical Recycling Plant 2 (Pathumthani/ Bangadhee)	Secure landfill Site ,Non-Recycling Process. (Ratchaburi/ Muang)
Started Point (Generation node)						
Bangkok	25.85	37.42	103.77	51.7	74.84	207.54
Nakhonpathom/Muang	86.8	78.88	46.69	173.6	157.76	93.38
Nonthaburi/Muang	45.8	20.43	106.64	91.6	40.86	213.28
Pathumthani/Muang	59.5	0	125.27	119	0	250.54
Samutprakarn/Muang	47.8	59.37	111.75	95.6	118.74	223.5
Samutsakhon/Muang	61.65	72.2	75.21	123.3	144.4	150.42
Recovery Plant (Samutsakhon)	43.78	72.2	-	87.56	144.4	-
Secure landfill Site ,Non-Recycling Process. (Ratchaburi/Muang)	111.75	125.27	-	223.5	250.54	-

Source: Department of Highway, Thailand, 2004.

4.5 Estimation of spent fluorescent lamp (SFL) loads.

Estimated amounts on SFL loads play an important role in environmental impact analysis. This section discusses background information regarding sources of waste (SFLs) and details a process of waste load estimation Firstly, the amount of SFLs generated from each province in the hypothetical network was estimated from the consumption of FLs associated with that area. Then, by encompassing the consumption data on FLs with the data on the life time of each FL, the amount of SFLs generated was declared. Also, the growth rates of SFLs in the case study areas were interpolated. Finally, both SFL loading and growth rate data were obtained.

4.5.1 Estimation of fluorescent lamps consumption

The fluorescent lamps consumed in Thailand have normally been supplied by Thai manufacturers, otherwise, by importing from foreign countries. As a result, the amount of fluorescents consumed nationwide was estimated by the following relationship equation:

Number of fluorescent lamps consumed nationwide

= Number of fluorescent lamps supplied from Thai manufactures

+ Number of fluorescent lamps imported from foreign countries (4.1)

The number of fluorescent lamps supplied from Thai manufactures was collected from the total number of fluorescents produced by all fluorescent manufacturers in Thailand. While that of fluorescents imported was collected from the Thai Customs Department. The results of the data collections are shown in Table 4.3

Table 4.3 The total amount of fluorescent lamps consumed each year in Thailand.

Year	Types of lamps	Number of FL produced in Thailand (per 1000 lamps)	Number of FL imported from foreign countries (per 1000 lamps)	Total number of FL consumption (per 1000 lamps)
2542	Tubular lamps (Fluorescent tube)	24,523	3,247	27,770
	Circline fluorescent lamps	4,691	325	5,016
	Compact fluorescent lamps	3,764	339	4,103
	Total	32,979	3,911	36,890
2543	Tubular lamps (Fluorescent tube)	26,041	4,732	30,773
	Circline fluorescent lamps	3,531	525	4,056
	Compact fluorescent lamps	4,135	1,442	5,577
	Total	33,707	6,699	40,406
2544	Tubular lamps (Fluorescent tube)	27,558	4,014	31,572
	Circline fluorescent lamps	2,372	401	2,773
	Compact fluorescent lamps	4,506	916	5,422
	Total	34,436	5,331	39,767
2545	Tubular lamps (Fluorescent tube)	30,294	3,274	33,568
	Circline fluorescent lamps	2,702	364	3,066
	Compact fluorescent lamps	5,049	1,419	6,468
	Total	38,045	5,057	43,102
2546	Tubular lamps (Fluorescent tube)	33,030	3,583	36,613
	Circline fluorescent lamps	3,031	398	3,429
	Compact fluorescent lamps	5,592	3,137	8,729
	Total	41,653	7,118	48,771

Source: CoCusi Coque (Thailand) Co., Ltd. Seminar document of pilot scale project for recycling spent fluorescent lamps in Thailand; 2004.

In addition, the data on average lifetimes of FLs was also collected. The overall average life time was then calculated as shown in Tables 4.4 and 4.5.

Of these, the minimum number of hours for the lifetime of each kind of FL was as follows: 10,000 hours for tubular lamps (fluorescent tube), 8,000 hours for circline fluorescent lamps and 6,000 hours for compact fluorescent lamps. When these data were integrated with the number of real average usage hours of a FL for each kind of source as shown in Table 4.4, the average using time or the average lifetime of an FL was calculated. The results are shown in Table 4.5.

Table 4.4 The average FL shelf life associated with each source type

Source	Hours/day	Days/week
Small office	8	5
Large office	10	5
Resident	17	7
Hotel	20	7
Factory	14	6
College	8	5
Hospital	15	7
Department Store	14	7
Convention Hall	14	6
Average	13	6

Source: CoCusi Coque (Thailand) Co., Ltd. Seminar document of pilot scale project for recycling spent fluorescent lamps in Thailand; 2004.

Table 4.5 Estimation of an average FL shelf-life

Kind of FL	Life time (Hrs)	Using time			Average using time (in years)
		Hours/day	Days/week	Hours/year	
Tubular lamps (Fluorescent tube)	10,000	13	6	4,056	2.5
Circline fluorescent lamps	8,000	13	6	4,056	2.0
Compact fluorescent lamps	6,000	13	6	4,056	1.5

Source: CoCusi Coque (Thailand) Co., Ltd. Seminar document of pilot scale project for recycling spent fluorescent lamps in Thailand; 2004.

4.5.2 Estimation of the amount of generated SFLs in the study areas

For managing wastes generated by SFLs for each province, data regarding the number of SFLs generated in each province was required. Unfortunately this data group was not obtainable at all, although the overall number of SFLs in Thailand was obtained as mentioned in the previous section. Hence, the proportion of the GDP of each province to the total GDP coupled with the total number of fluorescent lamps consumed in Thailand were used to approximate the number of SFLs generated in each province. The results can be seen in Table 4.6. Finally, making use of these numbers, a 20-year projection of SFLs available in each province was conducted using a regression analysis with a 2007-base year. The results of the projection provided information on the SFL loads and growth rates of each province, as depicted in Figure 4.2. Additionally, the projection equations predicting the SFL loads over the planning horizon were obtained as illustrated in Table 4.6. The information was important for a policy set up of SFL management over the planning horizon. The characteristics of the study areas described by the waste loads of SFLs and associated growth rates of each area are illustrated in Figure 4.3.

Table 4.6 Proportion of GDP of each province to the total GDP in Thailand and the number of SFLs

Year (FLs defined as waste (SFLs))	Year (FLs is started to use)	Value	Thailand	Bangkok	Nakhonpathom	Nonthaburi	Pathumthani	Samutprakarn	Samutsakhon
2545	2542	GDP	4637079	1482516	74231	64788	131683	300513	128595
		Ratio	1	0.32	0.02	0.01	0.03	0.06	0.03
		The amount SFLs *	27770	8878	445	388	789	1800	770
2546	2543	GDP	4922731	1579297	78447	65361	130458	328020	151732
		Ratio	1	0.32	0.02	0.01	0.03	0.06	0.03
		The amount SFLs *	30773	9873	490	409	816	2051	949
2547	2544	GDP	5133502	1656112	81991	69012	133864	350873	159322
		Ratio	1	0.32	0.02	0.01	0.03	0.06	0.03
		The amount SFLs *	31572	10185	504	424	823	2158	980
2548	2545	GDP	5446043	1673941	88866	72422	120633	370343	172018
		Ratio	1	0.32	0.02	0.01	0.03	0.06	0.03
		The amount SFLs *	33568	10318	548	446	744	2283	1060
2549	2546	GDP	5930362	1749548	99927	76162	133833	381261	193337
		Ratio	1	0.32	0.02	0.01	0.03	0.06	0.03
		The amount SFLs *	36613	10801	617	470	826	2354	1194

* = Unit equal Thousand Lamps

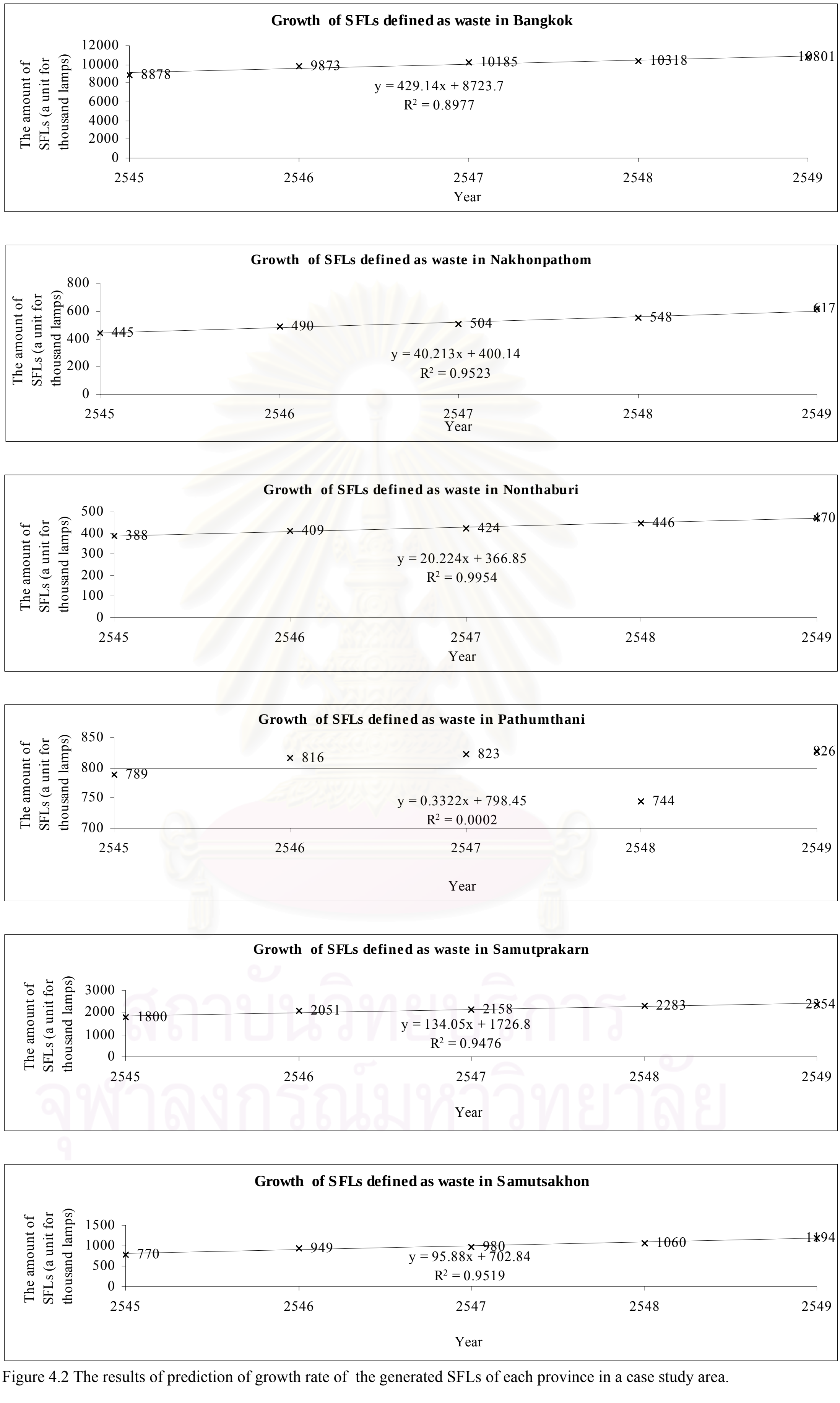
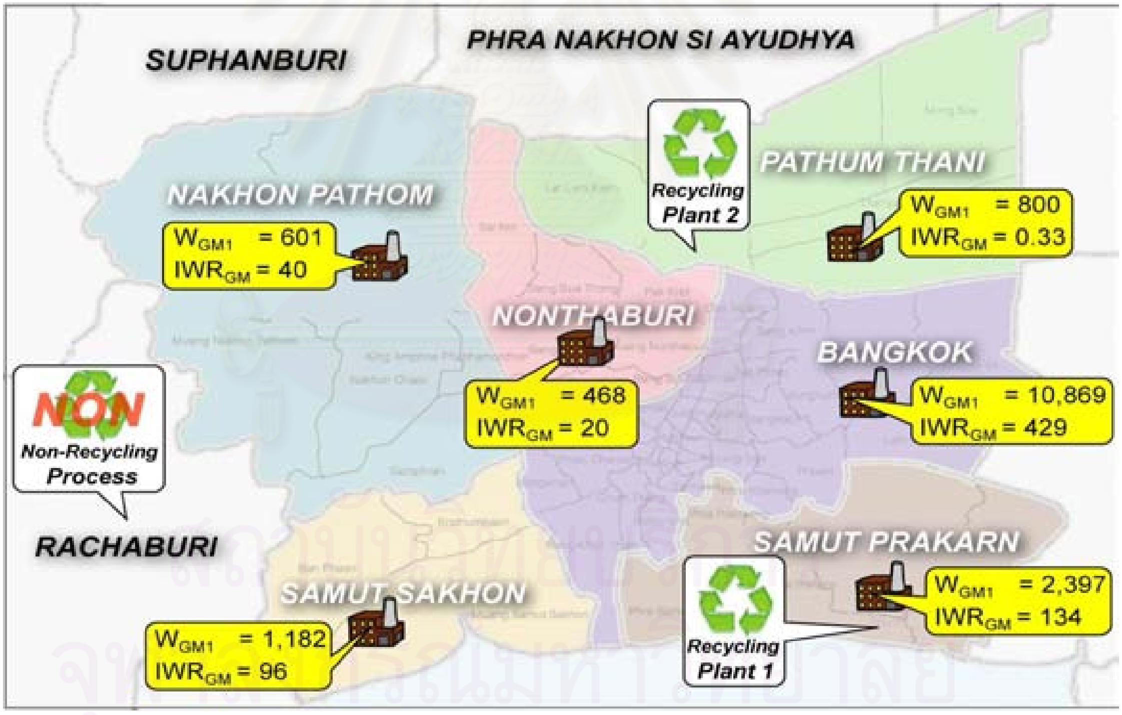


Figure 4.2 The results of prediction of growth rate of the generated SFLs of each province in a case study area.

Table 4.7 The numbers of SFLs and resulting growth rates for each province in the 2007-base year

Province	Initial number of SFLs (a thousand lamps) $W_{GM\,1}$	Growth rate (a thousand lamps per year) $IWR_{\,GM}$	Predicted number of SFSs in the 2007-base year (a thousand lamps)
Bangkok	8723.7	429.14	10869
Nakhonpathom	400.14	40.21	601
Nonthaburi	366.85	20.22	468
Pathumthani	798.45	0.33	800
Samutprakarn	1726.8	134.05	2397
Samutsakhon	702.84	95.88	1182

Figure 4.3 Diagram of the locations and the SFL loads as well as growth rates of SFL loads



CHAPTER V

MATHEMATICAL MODEL FORMULATION

On the basis of the life cycle assessment methodology and optimization concepts described in Chapter II coupled with the research methodology in Chapter III, as well as, data and information obtained in chapter IV, a mathematical model was developed. This model integrated other models of SFLs loads, inventory and associated impact assessment, and cost and benefit. All of these models were finally incorporated into a decision-making model. The model was designed to determine the optimal policy for the disposal of SFLs over the life-cycle chain. The objective of the model was to minimize global environmental impacts while meeting cost-benefit constraints. The optimal policy described whether to recycle or landfill; what recycling rates should be, if recycling; whether to expand or not expand capacities of the recycling or landfilling plants; what size capacities should be; and where to locate the plants.

5.1 Modeling the loads of SFLs

The loads of SFLs are important basic inputs to evaluate environmental impacts and costs as well as benefits incurred from disposal. As a result of the increase in demand, the growth rates of spent fluorescent lamps (IWR_{Gm}) associated with source nodes in the hypothetical network, which had been projected in Chapter 4, were taken into consideration for modeling the loads of SFLs. The model was formulated and associated with each node (Gm) and year (t) over the planning horizon. The resulting model is represented as follows:

$$W_{Gm\ t} = W_{Gm\ 1} + (t-1)\ (IWR_{Gm}) \qquad (5.1)$$

where

$W_{Gm\ t}$ = the amount of SFLs at generation node m (Gm) in year t.

$W_{Gm\ 1}$ = the amount of SFLs at generation node m in the first year.

IWR_{Gm} = the growth rate of SFLs at each generation node m.

t = the year (t =1, 2, 3, 4,…,T)

5.2 The inventory analysis models

Inventory analysis models, herein, identified materials and energy consumed, as well as pollutants emitted by all activities through the life cycle process chain of the SFLs. The major process activities included those which occurred in the processes of recycling, non-recycling, and transportation. As a result, the inventory models taken into consideration were divided into three categories: transportation, recycling and non-recycling processes.

5.2.1 The inventory models for the transportation processes

A transportation process is one activity in a life-cycle process chain of SFLs that generally has significant impacts on the environment. In this study, transportation processes occurred in four situations as illustrated in Figure 5.1 and described as follows:

- transport of SFLs from generation node (transfer stations) to recycling plants
- transport of SFLs from generation node to non-recycling plants
- transport of recovery materials from recycling plants to manufacturing plants for reuse as raw materials of new products
- transport of residual wastes generated from recycling plants to ultimate disposal sites

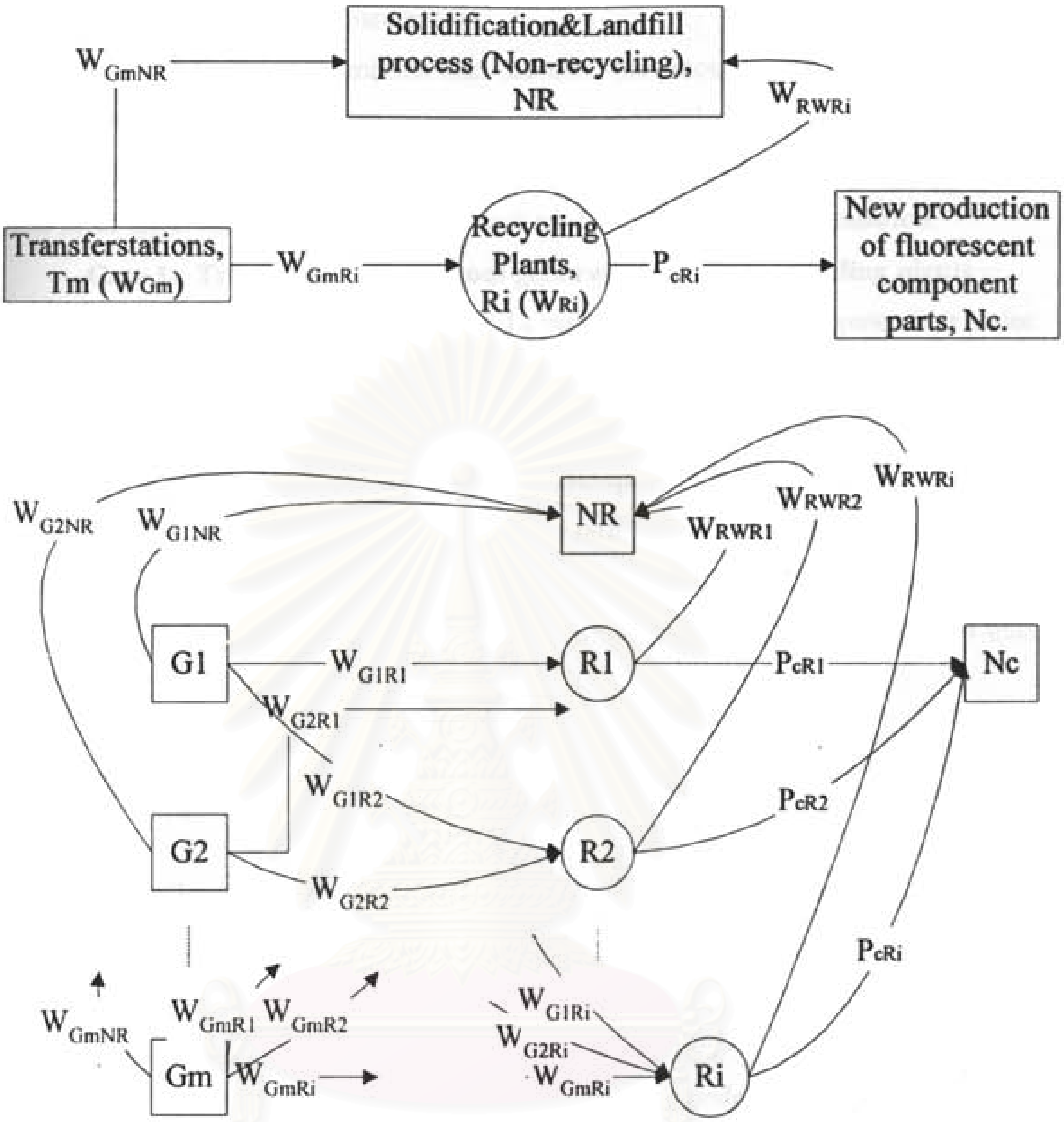


Figure 5.1 Transportation within the SFL life-cycle process chain

In general, a transportation process consumes energy and causes toxic-element emissions to the environment. However, in this study, energy consumption was disregarded for the two latter transportation situations because recovery-material and residual-wastes buyers were responsible for the energy consumption themselves, as is the current practice.

The amount of fuel consumption was determined by the fuel consumption rate and distance as well as the amount of SFLs as follows:

The amount of fuel consumption

$$= f\,(\text{fuel consumption rate, distance, the amount of SFLs}) \qquad (5.2)$$

The amount of fuel consumption, which was calculated from Equation 5.2, determined the inventory that arose from transportation processes and was further used as an input variable to formulate a cost model later on in the formulation.

Case 1: Transport of SFLs from generation nodes to recycling plants

For this transportation process, SFLs were collected from all generation nodes and then transferred to recycling plants. The inventory that affected the environment arose from fuel consumption and the loads of SFLs. Hence, the inventory was then described according to the amount of fuel consumption which was in turn calculated by a product function of a fuel consumption rate, the amount of SFLs sent to the recycling plant, as well as its associated distance. The function, which represented the inventory that occurred from transporting the SFLs to the recycling plant, was thus described below:

$$FC_{GmRi\ t} = FCR_{SFLs} \times W_{GmRi\ t} \times D_{GmRi} \qquad (5.3)$$

where

$FC_{GmRi\ t}$ = the amount of fuel consumed to transport SFLs from generation node m (Gm) to recycling plant i (Ri) at time t. (kg.)

$FCR_{SFLs\ tr}$ = the fuel consumption rate of a truck used for transporting SFLs (Lite/kg-km).

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t (kg.)

D_{GmRi} = the distance from generation node m to recycling plant i

I = the number of hypothetical recycling plants (i=1,2,3,4,…, I)

Case 2: The transportation of SFLs from generation node to non-recycling plants

In a similar manner, for those SFLs that were collected from generation nodes to be sent to non-recycling plants instead of recycling plants, the inventory was described by a product function of the fuel consumption rate, amount of SFLs transferring to the non-recycling plant, as well as its associated distance. The function representing the inventory which occurred from transporting the SFLs to the non-recycling plant was described below:

$$FC_{GmNR\ t} = FCR_{SFLs\ tr} \times W_{GmNR\ t} \times D_{GmNR} \tag{5.4}$$

where

$FC_{GmNR\ t}$ = the amount of fuel consumed to transport SFLs from generation node m (Gm) to non-recycling plant i (NRi) at time t. (kg.)

$FCR_{SFLs\ tr}$ = the fuel consumption rate of a truck used for transporting SFLs (Lite/kg-km).

$W_{GmNR\ t}$ = the amount of SFLs sent from generation node m to non- recycling plant i at time t (kg.)

D_{GmNR} = the distance from generation node m to non-recycling plant i

Case 3: The transportation of recovery materials from recycling plants to manufacturing plants for reuse as raw materials of new products

In this case, all types of recovery materials obtained from recycling plants were sold to manufacturers for reuse as raw materials for new products. As mentioned earlier, for this case energy consumption was not taken into consideration because buyers were responsible for transportation processes according to the current practice. The inventory for this type of transportation process was therefore described contrary to the first two cases. Nevertheless, this type of transportation still has impacts on the environment. Hence, the inventory that occurred by this type of transportation was determined.

The inventory was a function of only the amount of recovery materials obtained from the recycling plant and distance to a manufacturing firm that bought the recovery materials to use in the production of new products. Hence, the function representing the inventory associated with this transportation was described below:

$$D_{PRi\ t} = \sum_{(c = 1 \text{ to } C)} D_{Ri\ Nc} \times P_{cRi\ t} \tag{5.5}$$

$$P_{cRi\ t} = P_{Rc} \times W_{Ri\ t} \tag{5.6}$$

$$W_{Ri\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmRi\ t} \tag{5.7}$$

where

$DP_{Ri\ t}$ = the total amount of all kinds of recovery materials (c =1,2,…,C) transporting with a distance equal to that from recycling plants i and to manufacturing plants i for reuse as raw materials for new products at time t

$D_{Ri\ Nc}$ = the distance from recycling plant i to manufacturing plant Nc that bought the recovery material c, c=1,2,…,C

$P_{cRi\ t}$ = the amount of recovery material c produced by recycling plant i at time t

PR_c = the production rate of recovery material c obtained from recycling plant.

$W_{Ri\ t}$ = the total amount of SFLs sent to the recycling plant i at time t.

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

c = the number of types of recovery materials (c =1, 2, 3, 4,… ,C)

Case 4: The transportation of residual wastes generated from recycling plants to ultimate disposal

In this transportation process, residual wastes which occurred at the recycling plants were sold to agencies for ultimate disposal (waste stabilization and waste landfilling). In this study, it was assumed that there was only one selected landfill plant which was the same one that was presently in place. Similar to the previous case, fuel consumed was considered the responsibility of the outbound agencies. The inventory associated with this transportation thus relied upon only two factors of distance and transported loads.

The inventory was therefore a function of the amount of recovery materials obtained from the recycling plant and distance to the manufacturing firm that bought the recovery materials for the production of new products. Hence, the function representing the inventory associated with this transportation was described below:

$$DRW_{Ri\ NR\ t} = D_{Ri\ NR} \times W_{RWRi\ t} \tag{5.8}$$

$$W_{RWRi\ t} = RWPR \times W_{Ri\ t} \tag{5.9}$$

$$W_{Ri\ t} = \Sigma_{(m = 1 \text{ to } M)}\ W_{GmRi\ t} \tag{5.10}$$

where

$DRW_{Ri\ NR\ t}$ = the total amount of residual wastes transported with a distance equals to that from recycling plant i to landfill plant NR at time t

$D_{Ri\,NR}$ = the distance from recycling plant i to the landfill plant NR

$W_{RWRi\,t}$ = the amount of residue waste generated from recycling plant i at time t.

RWPR = the residual waste production rate at recycling plant.

$W_{Ri\,t}$ = the amount of SFLs at recycling plant i at time t.

$W_{GmRi\,t}$ = the amount of SFLs sending from generation node m to recycling at plant i at time t.

m = the number of SFL generation nodes (m =1, 2, 3, 4,…, M)

5.2.2 The inventory model of the recycling process

As stated in Chapter II, a recycling process generally contains three major activities. These include disassembly processes, waste separation, and residual disposal. In the recycling process, the recovery of materials for reuse as raw materials for new products may be obtained while residual wastes are transferred to disposal sites or landfills. All these activities consume materials and energy while emitting pollutants to the environment. For these reasons, materials and energy consumption, pollutant emissions, recovery materials and residual wastes (landfill or disposal) at the recycling plants were taken into consideration for inventory modeling associated with the recycling processes.

Case 1: Material and energy consumption inventory

This inventory which occurred at a recycling plant as a result of materials and energy consumption in a disassembly process was determined by the total amount of SFLs at the recycling plant and the rate of consumption per unit of SFLs.

$$C_{kRi\,t} = CF_{kR} \times W_{Ri\,t} \tag{5.11}$$

$$W_{Ri\,t} = \sum_{(m = 1 \text{ to } M)} W_{GmRi\,t} \tag{5.12}$$

where

$C_{kRi\,t}$ = the amount of material and energy type k consumed at recycling plant I at time t.

CF_{kR} = the consumption factor associated with raw material and energy type k at recycling plant.

$W_{Ri\,t}$ = the total amount of SFLs sent to recycling plant i at time t.

$W_{GmRi\,t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

k = the number of the types of material & energy consumed at each recycling plant (k =1, 2, 3, 4,… ,K)

Case 2: Emission inventory in a recycling process

As mentioned earlier, the disassembly process may induce pollutant emissions. The inventory obtained from this emission was defined by the emission factor and the amount of SFLs at the recycling plant as follows:

$$E_{pRi\,t} = EF_{pR} \times W_{Ri\,t} \tag{5.13}$$

$$W_{Ri\,t} = \sum_{(m=1 \text{ to } M)} W_{GmRi\,t} \tag{5.14}$$

where

$E_{pRi\,t}$ = the amount of pollutant emission type p at recycling plant i at time t.

EF_{pR} = the emission factor of pollutant kind p at recycling plant (the emission rate)

$W_{Ri\,t}$ = the total amount of SFLs sent to recycling plant i at time t.

$W_{GmRi\,t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

p = the number of types of pollutants emitted from each recycling plant (p =1, 2, 3, 4,…, P)

Case 3: Recovery material inventory

In the recycling process, the process not only emitted pollutants into the environment, but it also produced recovery materials. These recovery materials were sold to manufacturing firms to reuse as raw materials for new products. The recovery material inventory was determined by the following equations:

$$P_{cRi\,t} = PR_c \times W_{Ri\,t} \tag{5.15}$$

$$W_{Ri\,t} = \sum_{(m=1 \text{ to } M)} W_{GmRi\,t} \tag{5.16}$$

where

$P_{cRi\ t}$ = the amount of recovery material type c produced at recycling plant i at time t**.**

PR_c = the production rate of recovery material type c from recycling plant.

$W_{Ri\ t}$ = the total amount of SFLs sent to recycling plant i at time t.

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i, at time t.

c = the number of types of recovery materials (c =1, 2, 3, 4,… , C)

Case 4: Residual waste inventory

In addition to the recovery materials mentioned above, the recycling process may generate residual wastes. Some of these wastes were finally transferred to be stabilized and sent to a landfill.

a) Residual wastes generated

The amount of the residual wastes generated at the recycling plant was assumingly written as a linear function of the total amount of SFLs at the recycling plant and unit rate of residual waste production. In other words, the residual waste inventory was defined as:

$$W_{RWRi\ t} = RWPR \times W_{Ri\ t} \tag{5.17}$$

$$W_{Ri\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmRi\ t} \tag{5.18}$$

where

$W_{RWRi\ t}$ = the amount of generated residual wastes generated at recycling plant i at time t.

RWPR = the residual waste production rate from recycling plant.

$W_{Ri\ t}$ = the total amount of SFLs sent to recycle at recycling plant i at time t.

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

b) Ultimate disposal inventory

In general, the generated residual wastes from the recycling plant were sent to an ultimate disposal site for stabilizing and landfilling. This ultimate disposal process always consumes both materials and energy. In this study, the ultimate disposal inventory was written as a function of consumption factors and residual wastes generated by the recycling plant as described by:

$$CRW_{lS\ t} = \sum_{(i = 1 \text{ to } I)} [CF_{lS} \times W_{RWRi\ t}] \qquad (5.19)$$

where

$CRW_{lS\ t}$ = the amount of material type l or energy type l consumed in the ultimate disposal residue waste from recycling process at time t.

CF_{lS} = the material type l or energy type l consumption factors used in ultimate disposal process at the recycling plant

I = the number of types of recycling plants.

l = the number of type of materials & energy consumed for the ultimate disposal of residual waste at stabilization plant (l =1, 2, 3, 4,… ,L)

Case 5: Emission inventory at an ultimate disposal site

In the ultimate disposal process, pollutants may be emitted into the environment. The amount of the pollutant emission was a function of an emission factor and the amount of residual wastes generated at the recycling plan. The emission inventory at the ultimate disposal site was therefore described by the following equation:

$$ERW_{rS\ t} = \sum_{(i = 1 \text{ to } I)} [EF_{rS}\ \ W_{RWRi\ t}] \qquad (5.20)$$

where

$ERW_{rS\ t}$ = the amount of type r-pollutant emission from ultimate disposal residue waste from recycling process at time t.

EF_{rS} = the emission factor of pollutant type r from ultimate disposal residue waste from recycling process.

r = the number of types of pollutants emitted from ultimate disposal residual waste at stabilization plant (r =1, 2, 3, 4,… ,R)

5.2.3 An inventory model of a non-recycling process

In a non-recycling process, the SFLs were sent through crushing and stabilization processes before landfilling. In this process, materials and energy were consumed at a non-recycling plant. In addition, it also generates pollutants that have impacts on the environment. The amount of material type n or energy type n consumed at a non-recycling plant at time t ($C_{nS\ t}$) was also modeled as a function of the amount of SFLs generated at the non-recycling plant in the following equation:

$$C_{nS\ t} = CF_{nS} \times W_{NR\ t} \tag{5.21}$$

$$W_{NR\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmNR\ t} \tag{5.22}$$

where:

$C_{nS\ t}$ = the amount of material type n or energy type n consumed at a non-recycling plant at time t.

CF_{nS} = the consumption factor of raw material and energy type n at solidified plant.

$W_{NR\ t}$ = the total amount of SFLs sent to non- recycling plant at time t.

$W_{GmNR\ t}$= the amount of SFLs sent from generation node m to non- recycling plant at time t.

n = the number of types of materials & energy consumed at non-recycling plant (n =1, 2, 3, 4,…, N).

At the same time, the process generated pollutants where the amount of pollutant type o emissions at a solidified plant at time t ($E_{oS\ t}$) was a function of wastes generated at the non-recycling plant as shown below:

$$E_{oS\ t} = EF_{oS} \times W_{NR\ t} \tag{5.23}$$

$$W_{NR\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmNR\ t} \tag{5.24}$$

where

$E_{oS\ t}$ = the amount of type o-pollutant emissions at solidified plant at time t.

EF_{oS} = the emission factor of type o-pollutant at a non-recycling plant.

$W_{NR\ t}$ = the total amount of SFLs sent to non- recycling plant at time t.

$W_{GmNR\ t}$= the amount of SFLs sent from generation node m to a non- recycling plant at time t.

o = the number of types of pollutants emitted from a non-recycling plant ($o = 1, 2, 3, 4, \ldots, O$)

The amount of materials extracted instead of the loss of recovery materials was required to assess because the recovery material would be lost if the non-recycling process were worked out. The amount of these extracted materials type c is the function of $W_{GmNR\ t}$.

$$P_{cNR\ t} = PR_c \times W_{NR\ t} \quad (5.25)$$

$$W_{NR\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmNR\ t} \quad (5.26)$$

where

$P_{cNR\ t}$ = the amount of recovery material type c which were sent to non-recycling process at time t.

PR_c = the production rate of recovery material type c from recycling plant.

$W_{NR\ t}$ = the total amount of SFLs sent to non- recycling plant at time t.

$W_{GmNR\ t}$= the amount of SFLs sent from generation node m to non- recycling plant at time t.

5.3 An environmental impact assessment model

Making use of the inventory models developed in the previous section, an environmental impact assessment model was developed by linking inventory models with environmental impact models. The model coupled with the Eco-indicator 99 was then employed to assess the environmental impacts. The environmental impacts were calculated as a single score unit. The computation was divided into four steps including characterization, damage assessment, normalization, and weighing.

Starting with the characterization, the amounts of materials and energy consumed were translated into the amount of environmental impacts using characterization factors. The assessment relied on productions of material, energy consumed, and pollutants released from all concern activities in the system boundary. It was conducted in three kinds of units. Then the damage assessment was conducted by making use of the resulting impact category indicators obtained from the previous step. There were three damage categories considered. The first was Human Health (HH) which is generally evaluated in the unit of DALY (=Disability adjusted life year), where different disabilities caused by diseases were weighed. The second was the Ecosystem **Q**uality (EQ) which is generally assessed in the unit of PDF*m^2yr (PDF= Potentially Disappeared Fraction of plant species). The last damage evaluated was the Resource (R) assessed in the unit of MJ (surplus energy, additional energy requirement to extract a kg of a mineral in the future).

Finally, normalization and weighing of those impacts were conducted, respectively, as a result of their different measurement indicator units and different impact potential. In conclusion, the damage assessment factors, normalization factors, and weighing factors were employed to convert all kinds of environmental impacts to the same unit (in a single score unit), based upon the Eco-indicator 99.

In this study, the environmental impacts which occurred in the SFLs disposal network were composed of three main parts related to environmental impacts caused by transportation processes, disassembly processes, and stabilization and solidification processes.

5.3.1 The environmental impact assessment model for transportation processes

In the transportation processes, the amounts of environmental impacts were composed of four main parts corresponding to the four types of transportation inventory models.

Case 1: Environmental impacts that arose during transportation of SFLs from generation nodes to recycling plants

The first part was the amount of environmental impacts which occurred from the transportation of SFLs from generation nodes to recycling process plants at time t ($ETWR_t$) which was a product function of the amount SFLs sent from the generation node to the recycling plant and the transported distance (between generation node and recycling plants). Also, the characterization factor ($C_{T\ tr\ j}$), damage assessment factors ($D_{T\ tr\ j}$), normalization values of all kinds of environmental impacts ($N_{T\ tr\ j}$) and associated weighing values ($W_{T\ tr\ j}$) were parameters of the designed function. The resulting formulation was expressed by:

$$ETWR_{t} = \sum_{(m = 1 \text{ to } M,\ i = 1 \text{ to } I)} ETW_{GmRi\ t} \qquad (5.27)$$

$$ETW_{GmRi\ t} = \sum_{(j = 1 \text{ to } J)} (W_{GmRi\ t} \times D_{GmRi\ t} \times C_{T\ tr\ j} \times D_{T\ tr\ j} \times N_{T\ tr\ j} \times W_{T\ tr\ j}) \qquad (5.28)$$

where

$ETWR_{t}$ = the total environmental impacts which occurred from transporting SFLs from all generation nodes to all recycling plants at time t.

$ETW_{GmRi\ t}$ = the environmental impacts which occurred from transporting SFLs from generation node m to recycling plant i at time t.

$C_{T\ tr\ j}$ = the characterization factor

$D_{T\ tr\ j}$ = the damage assessment factor (for transportation of material by truck type tr).

$N_{T\ tr\ j}$ = the normalization value of environmental impact type j (for transportation of material by truck type tr).

$W_{T\ tr\ j}$ = the weighing value of environmental impact type j (for transportation of material by truck type tr).

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t (kg.)

D_{GmRi} = the distance from generation node m to recycling plant i

j = the number of types of environmental impacts (j=1,2,3,4,…,J)

Case 2: Environmental impacts which arose during the transportation of SFLs from generation nodes to non-recycling plants

The second part was the environmental impacts generated from the transportation of SFLs from the generation node to a non-recycling process each time. The total environmental impact which occurred during the transporting of SFLs from all generation nodes to non-recycling plants at time t ($ETWNR_{t}$) was a function of the amount of SFLs sent from generation node to non-recycling plants, transportation distances (between generation node m to a non-recycling plant), characterization and damage factors, normalization and weighing values. The function was described as follows:

$$ETWNR_{t} = \sum_{(m = 1 \text{ to } M)} ETW_{GmNR\ t} \qquad (5.29)$$

$$ETW_{GmNR\ t} = \sum_{(j = 1 \text{ to } J)} (W_{GmRi\ t} \times D_{GmNR\ t} \times C_{T\ tr\ j} \times D_{T\ tr\ j} \times N_{T\ tr\ j} \times W_{T\ tr\ j}) \qquad (5.30)$$

where

$ETWNR_t$ = the total environmental impact generated from transporting SFLs from all generation nodes to non-recycling plant at time t.

$ETW_{GmNR\ t}$ = the environmental impacts generated from transporting SFLs from generation node m to non-recycling plant at time t.

Case 3: Environmental impacts which arose during the transportation of recovery materials from recycling plants to manufacturing plants

The environmental impacts which arose from the transporting of recovery materials to manufacturing plants at time t ($ETPR_t$) for the production of new products was evaluated in a similar manner as in the first and second cases. The environmental impact was a function of all the amount of recovery materials, distance from recycling plants to manufacturing firms, characterization and damage assessment factors, normalization and weighing values. The function was expressed as follows:

$$ETPR_t = \sum_{(i = 1 \text{ to } I)} ETP_{Ri\ t} \tag{5.31}$$

$$ETP_{Ri\ t} = \sum_{(j = 1 \text{ to } J)} (D_{RiNc\ t} \times P_{cRi\ t} \times C_{T\ tr\ j} \times D_{T\ tr\ j} \times N_{T\ tr\ j} \times W_{T\ tr\ j}) \tag{5.32}$$

where

$ETPR_t$ = the environmental impacts that arose from the transportation of recovery materials from all recycling plants to a manufacturing plant of new products at time t.

$ETP_{Ri\ t}$ = the environmental impact that arose from the transportation of recovery materials from recycling plant i to new product manufacturing plant at time t.

$D_{RiNc\ t}$ = Distance (between recycling plant i, Ri, and new product type c manufacturing plant, Nc)

$P_{cRi\ t}$ = the amount of recovery material type c produced from recycling plant i at time t.

Case 4: Environmental impacts which arose from the transportation of residue wastes from recycling plants to ultimate disposal sites

Similar to all the above cases, the environmental impacts which arose from the ultimate disposal processes of waste residue were determined by all the amount of waste residue, distance from recycling plants to the disposal site, characterization and damage assessment factors, normalization and weighing values, as seen in the following equations:

$$ETRW_t = \sum_{(i = 1 \text{ to } I)} ETRW_{Ri\ t} \quad (5.33)$$

$$ETRW_{Ri\ t} = \sum_{(j = 1 \text{ to } J)} (D_{Ri\ NR} \times W_{RWRi\ t} \times C_{T\ tr\ j} \times D_{T\ tr\ j} \times N_{T\ tr\ j} \times W_{T\ tr\ j}) \quad (5.34)$$

where

$ETRW_t$ = the total environmental impact from the transportation of residue waste from recycling plant to ultimate disposal process (stabilization, solidification and landfill) at time t.

$ETRW_{Ri\ t}$ = the environmental impact from the transportation of residue waste from recycling plant i, Ri, to ultimate disposal process (stabilization, solidification and landfill) at time t.

$D_{Ri\ NR}$ = the distance from recycling plant i to the landfill plant NR

$W_{RWRi\ t}$ = the amount of residue waste generated from recycling plant i at time t.

5.3.2 An environmental impact assessment model of the recycling process

In this part, the number of environmental impacts which occurred was divided into two parts. The first part included environmental impacts that resulted from the production of raw material and energy used in the disassembly process of the recycling plant at time t and from all pollutant emissions at all recycling plants at any time t.

The first environmental impacts were determined by a function of recovery inventory, characterization and damage factors, and normalization and weighing values as described in the equations below:

$$ECR_t = \sum_{(i = 1 \text{ to } I)} EC_{Ri\ t} \quad (5.35)$$

$$EC_{Ri\ t} = \sum_{(k = 1 \text{ to } K)} EC_{kRi\ t} \quad (5.36)$$

$$EC_{kRi\ t} = \sum_{(j = 1 \text{ to } J)} (C_{kRi\ t} \times C_{kj} \times D_{kj} \times N_{kj} \times W_{kj}) \quad (5.37)$$

where

ECR_t = the total environmental impacts which resulted from the production of all kinds of materials and energy consumed by all recycling plants at time t.

$EC_{Ri\,t}$ = the total environmental impacts which resulted from the extraction of all kinds of materials & energy consumed by recycling plant i at time t.

$EC_{kRi\,t}$ = the environmental impacts which resulted from the extraction of material type k or energy type k consumed by recycling plant i at time t.

$C_{kRi\,t}$ = the amount of material type k or energy type k consumed at recycling plant i at time t.

C_{kj} = the characterization factors

D_{kj} = the damage assessment factor (for used raw material or energy k).

N_{kj} = the normalization value of environmental impacts kind j (for used raw material or energy k).

W_{kj} = the weighing value of environmental impacts type j (for used raw material or energy k).

The second part involved the amount of environmental impacts which occured from the emissions of pollutants given off during the recycling process which was a function of emission inventory, characterization and damage factors, and normalization and weighing values as seen in the following equations:

$$EER_t = \sum_{(i = 1 \text{ to } I)} EE_{Ri\,t} \tag{5.38}$$

$$E_{Ri\,t} = \sum_{(p = 1 \text{ to } P)} EE_{pRi\,t} \tag{5.39}$$

$$EE_{pRi\,t} = \sum_{(j = 1 \text{ to } J)} (E_{pRi\,t} \times C_{pj} \times D_{pj} \times N_{pj} \times W_{pj}) \tag{5.40}$$

where

EER_t = the total environmental impacts which occured from all pollutant emissions at all recycling plants at time t.

$EE_{Ri\,t}$ = the total environmental impacts which occured from pollutant emissions at each recycling plant i at time t.

$EE_{pRi\,t}$ = the environmental impact which occured from pollutant type p emission at recycling plant i at time t.

$E_{pRi\ t}$ = the amount of pollutant emission type p at recycling plant i, Ri, at time t.

C_{pj} = the characterization factor (showing environmental impact type j in unit of equivalent per amount of pollutant emission type p).

D_{pj} = the damage assessment factor (for pollutant emission type p).

N_{pj} = the normalization value of environmental impact type j (for pollutant emission type p).

W_{pj} = the weighing value of environmental impact type j (for pollutant emission type p).

Additionally, the residue wastes released from the disassembly process require stabilization and solidification before landfill. Hence, the amount of environmental impacts which arose from the ultimate disposal of residual wastes from a recycling plant at time t was also taken into account. The total environmental impact incurred from the production of all material and energy consumed in the ultimate disposal of residue wastes from the recycling process at time t ($ECRWS_t$) was a function of the amount of all material and energy consumed in the process of the ultimate disposal of residue wastes as seen below:

$$ECRWS_t = \sum_{(l = 1 \text{ to } L)} ECRW_{lS\ t} \tag{5.41}$$

$$ECRW_{lS\ t} = \sum_{(j = 1 \text{ to } J)} (CRW_{lS\ t} \times CRW_{lj} \times DRW_{lj} \times NRW_{lj} \times WRW_{lj}) \tag{5.42}$$

$$EE_{pRi\ t} = \sum_{(j = 1 \text{ to } J)} (E_{pRi\ t} \times C_{pj} \times D_{pj} \times N_{pj} \times W_{pj}) \tag{5.43}$$

where

$ECRWS_t$= the total environmental impacts generated by extraction of all material and energy consumption in the ultimate disposal of residue wastes from the recycling process at time t.

$ECRW_{lS\ t}$= the environmental impacts generated by extraction of materials and energy consumption in the ultimate disposal of residue wastes from the recycling process at time t.

$CRW_{lS\ t}$ = the amount of materials and energy consumption in the ultimate disposal of residue wastes from the recycling process at time t.

CRW_{lj} = the characterization factor showing environmental impact type j in a unit of equivalent per amount of used raw material or energy type l for the ultimate disposal of residual waste from the recycling process.

DRW_{lj} = the damage assessment factor (for used raw material or energy l).

NRW_{lj} = the normalization value of environmental impact type j (for used raw material or energy type l).

WRW_{lj} = the weighing values of environmental impacts type j (for used raw material or energy type l).

In addition, the total environmental impacts that occured from all pollutant emissions in the ultimate disposal of residue wastes from the recycling process at time t ($EERWS_t$) was a function of the amount of pollutant emissions from the ultimate disposal residue wastes ($ERW_{rS\,t}$), as follows:

$$EERWS_t = \Sigma_{(r = 1 \text{ to } R)} EERW_{rS\,t} \qquad (5.44)$$

$$EERW_{rS\,t} = \Sigma_{(j = 1 \text{ to } J)} (ERW_{rS\,t} \times C_{rj} \times D_{rj} \times N_{rj} \times W_{rj}) \qquad (5.45)$$

where

$EERWS_t$ = the total environmental impacts which resulted from all pollutant emissions from the ultimate disposal of residue wastes from th recycling process at time t.

$EERW_{rS\,t}$ = the total environmental impacts which resulted from pollutant type r emissions from the ultimate disposal of residue wastes from the recycling process at time t.

$ERW_{rS\,t}$ = the amount of pollutant emissions type r emitted from the ultimate disposal of residue wastes from the recycling process at time t.

C_{rj} = the characterization factor (showing environmental impact type j in unit of equivalent per amount of pollutant emission type r from the ultimate disposal of residue waste from the recycling process).

D_{rj} = the damage assessment factor (for pollutant emission type r).

N_{rj} = the normalization values of environmental impacts type j (for pollutant emission type r).

W_{rj} = the weighing values of environmental impacts type j (for pollutant emission type r).

5.3.3 The environmental impact assessment model in a non-recycling process

The environmental impact which resulted from the solidification and stabilization processes at time t depended on the amount of all materials and energy consumed by the solidified plant at time t ($C_{nS\ t}$) and the amount of all pollutant emissions at the solidified plant at time t ($E_{oS\ t}$). Therefore, this environmental impact was calculated as follows:

$$ECS_t = \sum_{(n = 1 \text{ to } N)} EC_{nS\ t} \tag{5.46}$$

$$EC_{nS\ t} = \sum_{(j = 1 \text{ to } J)} (C_{nS\ t} \times C_{nj} \times D_{nj} \times N_{nj} \times W_{nj}) \tag{5.47}$$

where

ECS_t = the total environmental impact which resulted from the extraction of all material and energy consumed in the solidified plant at time t.

$EC_{nS\ t}$ = the environmental impacts which resulted from the extraction of material type n or energy type n of the solidified plant at time t.

$C_{nS\ t}$ = the amount of material type n or energy type n comsumed at the solidified plant at time t.

C_{nj} = the characterization factor (showing environmental impact type j in unit of equivalent per amount of used raw material or energy type n).

D_{nj} = the damage assessment factor (for used raw material or energy type n).

N_{nj} = the normalization value of environmental impact type j (for used raw material or energy type n).

W_{nj} = the weighing value of environmental impact type j (for used raw material or energy type n).

$$EES_t = \sum_{(o = 1 \text{ to } O)} EE_{oS\ t} \tag{5.48}$$

$$EE_{oS\ t} = \sum_{(j = 1 \text{ to } J)} (E_{oS\ t} \times C_{oj} \times D_{oj} \times N_{oj} \times W_{oj}) \tag{5.49}$$

where

EES_t = the total environmental impacts which arose from pollutant emissions in the non-recycling plant at time t.

$EE_{oS\ t}$ = the environmental impacts which arose from pollutant type o emissions at the non-recycling plant at time t.

$E_{oS\ t}$ = the amount of pollutant type o emissions at the solidified plant at time t.

C_{oj} = the characterization factor (showing environmental impact type j in unit of equivalent per amount of pollutant type o emissions).

D_{oj} = the damage assessment factor (for used raw material or energy type o).

N_{oj} = the normalization value of environmental impact kind j (for used raw material or energy type o).

W_{oj} = the weighing value of environmental impact type j (for used raw material or energy type o).

At the same time, the amount of environmental impacts which occurred from the production the new material instead of from the loss of recovery material during the non-recycling process at time t ($ELRP_t$) was a function of $P_{cNR\ t}$ which was a variable received from the inventory process as shown in following equations:

$$ELRP_t = \sum_{(c = 1 \text{ to } C)} ELRPc_t \tag{5.50}$$

$$ELRPc_t = \sum_{(j = 1 \text{ to } J)} (P_{cNR\ t} \times C_{lr\ j} \times D_{lr\ j} \times N_{lr\ j} \times W_{lr\ j}) \tag{5.51}$$

where

$ELRP_t$ = the total environmental impact which arose from the production of all recovery materials which were sent to the landfill at time t.

$ELRPc_t$ = the environmental impact which arose from the production of new raw material type c instead of from the loss of recovery material type c which were sent to the landfill at time t.

$P_{cNR\ t}$ = the amount of recovery material type c which were not sent for recovery at time t.

$C_{lr\ j}$ = the characterization factor (showing environmental impact type j in unit of equivalent per amount of new production of recovery material type c).

$D_{lr\ j}$ = the damage assessment factor (for the new production of recovery material type c).

$N_{lr\ j}$ = the normalization value of environmental impact type j (for the new production of recovery material type c).

$W_{lr\,j}$ = the weighing value of environmental impact type j (for the new production of recovery material type c).

5.4 The Cost Model

This section discusses the development of the cost & benefit models for the management of the disposal of SFLs at various recycling rates. The cost-benefit models were created as constraint functions for setting up the optimum SFL recycling policy in the next chapter. The cost model consisted of factors related to transportation and recycling, as well as non-recycling.

5.4.1 The transportation cost function

In this study, the transportation costs consisted of fuel consumption excluding labor and maintenance costs. The cost of fuel consumption was in turn examined by the price and amount of fuel consumption. In addition, the transportation costs were focused only on those for transferring from generation nodes to recycling and non-recycling plants, as stated in 5.2.1. Alternately, costs due to the transportation of recovery materials from recycling plants to manufacturing firms for new production or to disposal sites were disregarded because those were the responsibility of the buyers.

a) Cost of transporting SFLs from generation node to recycling plants.

$$CTWR_t = \sum_{(m = 1 \text{ to } M,\ i = 1 \text{ to } I)} FC_{GmRi\ t} \times F \qquad (5.52)$$

where

$CTWR_t$ = the total cost incurred from the transportation of SFLs from all generation nodes to all recycling plants at time t.

$FC_{GmRi\ t}$ = the amount of fuel consumed by transportation of SFLs from generation node m to recycling plant i at time t.

F = the price of fuel used in the transportation.

b) Cost of transporting SFLs from generation node to non-recycling plants.

$$CTWNR_t = \sum_{(m = 1 \text{ to } M)} FC_{GmNR\ t} \times F \qquad (5.53)$$

where

$CTWR_t$= the total cost which arose from transporting SFLs from all generation nodes to non-recycling plant, NR at time t.

$FC_{GmNR\ t}$= the amount of fuel consumed by the transportation of SFLs from generation node m, Gm, to non-recycling plant, NR at time t.

F = Price of fuel used in the transportation.

5.4.2 The cost of the recycling process

The total cost in this part was divided into three main parts which included investment costs, operating and maintenance costs, and land costs.

The investment costs consisted of machine and construction costs. The costs related to that arose from expanding the capacities of all the recycling plants at time t. ($ECap_{Ri\ t}$). The cost function was therefore represented by the following:

$$CIR_t = \sum_{(i=1 \text{ to } I)} CI_{Ri\ t} \tag{5.54}$$

$$CI_{Ri\ t} = (CI_M + CI_C) \times ECap_{Ri\ t} \tag{5.55}$$

$$ECap_{Ri\ t} = W_{Ri\ t} / AUW \tag{5.56}$$

where

CIR_t = the investment costs of all recycling plants at time t.

$CI_{Ri\ t}$ = the investment costs of the recycling plant i, Ri, at time t.

$ECap_{Ri\ t}$ = the additional capacities required at recycling plant i at time t.

CI_M = the unit machine costs for adding capacity at time t.

CI_C = the unit construction costs for adding capacity at time t.

$W_{Ri\ t}$ = the total amount of SFLs sent to the recycling plant i, Ri, at time t.

AUW = the maximum capacity of a recycling plant.

For the operating costs, the amounts of all materials and energy consumption were taken into consideration. The operating costs function was therefore represented by the following equations:

$$CCR_t = \sum_{(i=1 \text{ to } I)} CC_{Ri\ t} \tag{5.57}$$

$$CC_{Ri\ t} = \sum_{(k=1 \text{ to } K)} (C_k R_{i\ t} \times C_k) \tag{5.58}$$

where

CCR_t = the total costs incurred by all material and energy consumption of all recycling plants at time t.

$CCR_{i\,t}$ = the total costs incurred by all material and energy consumption of recycling plant i at time t.

C_k = the price of each material and energy

$C_kR_{i\,t}$ = the amount of all material or energy consumed at recycling plant i at time t.

Additionally, the labor and maintenance costs were formulated as a function of $W_{GmRi\,t}$., assuming that unit labor costs and unit maintenance costs were constant parameters of the cost function. These two costs were then described by the following:

$$CLR_t = \sum_{(i = 1 \text{ to } I)} CL_{Ri\,t} \qquad (5.59)$$

$$CL_{Ri\,t} = (LCF_R + MCF_R) \times W_{Ri\,t} \qquad (5.60)$$

$$W_{Ri\,t} = \sum_{(m = 1 \text{ to } M)} W_{GmRi\,t} \qquad (5.61)$$

where

CLR_t = the total labor costs incurred associated with all recycling plants at time t.

$CL_{Ri\,t}$ = the labor costs associated with each recycling plant i at time t.

LCF_R = the unit labor costs associated with each recycling plant.

MCF_R = the unit maintenance costs associated with each recycling plant.

$W_{Ri\,t}$ = the total amount of SFLs sent to recycling plant i at time t.

$W_{GmRi\,t}$ = the amount of SFLs sent from generation node m, Gm, to recycling plant i at time t.

Furthermore, in this study, land costs associated with all recycling plants were determined by the rent cost data since the land cost data was not obtainable. The costs were estimated as follows:

$$CLRR_t = \sum_{(i = 1 \text{ to } I)} CLR_{Ri\,t} \qquad (5.62)$$

$$CLR_{Ri\,t} = (LRCF_R) \times ECap_{Ri\,t} \qquad (5.63)$$

$$ECap_{Ri\,t} = W_{Ri\,t} / AUW \qquad (5.64)$$

where

$CLRR_t$ = the land rent costs of all recycling plants at time t.

$CLR_{Ri\,t}$ = the land rent cost of recycling plant i, Ri, at time t.

$LRCF_R$ = the unit land rent cost per capacity expanded at recycling plant i

$ECap_{Ri\,t}$ = the amount of added capacity required by recycling plant i at time t.

$W_{Ri\,t}$ = the total amount of SFLs sent to recycling plant i, Ri, at time t.

AUW = the maximum capacity of a recycling plant.

However, the recycling process still generated residue wastes during the disassembly process as mentioned earlier. Therefore, the costs generated from the ultimate disposal of residual waste from the recycling plant at time t were taken into account. The total costs that arose from the disposal of residual waste (RW) were then determined as follows:

$$CRW_t = CRWR \times W_{RW\,t} \tag{5.65}$$

$$W_{RW\,t} = \sum_{(i = 1 \text{ to } I)} W_{RWRi\,t} \tag{5.66}$$

$$W_{RWRi\,t} = RWPR \times W_{Ri\,t} \tag{5.67}$$

$$W_{Ri\,t} = \sum_{(m = 1 \text{ to } M)} W_{GmRi\,t} \tag{5.68}$$

where

CRW_t = the total cost for disposal of residual waste(RW) at all recycling plants at time t.

CRWR= the market price rate for disposal of residual waste.

$W_{RW\,t}$ = the total amount of RW generated from all recycling plants at time t.

$W_{RWRi\,t}$ = the amount of generated residue waste from recycling plant i at time t.

RWPR = the residual waste production rate at the recycling plant.

$W_{Ri\,t}$ = the amount of SFLs at recycling plant i at time t.

$W_{GmRi\,t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

5.4.3 The cost of the non-recycling process

Furthermore, the costs incurred by the disposal of SFLs in a non-recycling process were expressed by the following equations;

$$CNR_t = CNRR \times W_{NR\ t} \tag{5.69}$$

$$W_{NR\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmNR\ t} \tag{5.70}$$

where

CNR_t = the total costs for SFL disposal in the non-recycling process at time t.

CNRR = the market price for disposal by a non-recycling process.

$W_{NR\ t}$ = the total amount of SFLs sent to a non- recycling plant at time t.

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

5.5 The benefits of SFL recycling

In this study, there were two types of benefits incurred by the SFL recycling process. The first benefit was incurred by the revenue generated by the SFL disposal service. The SFLs generator would be forced to pay for their generated waste disposal. These benefits were thus determined as a function of the amount of SFLs generated at each node, the amount of waste disposal, and market price for the disposal, as described below:

$$BSFLG_t = \sum_{(m = 1 \text{ to } M)} B_{Gm\ t} \tag{5.71}$$

$$B_{Gm\ t} = BR_{SFLG} \times W_{Gm\ t} \tag{5.72}$$

where

$BSFLG_t$ = th total revenue obtained from SFL generators at time t.

$B_{Gm\ t}$ = the market price for the disposal SFLs at time t.

BR_{SFLG}= the total amount of SFLs disposed of at time t.

$W_{Gm\ t}$ = the amount of SFLs at generation node m at time t.

The second benefit was obtained by selling recovery materials to manufacturing firms for reuse of recovery materials as raw materials for new products. Therefore, it was a function of the amount of waste generated at each node, $W_{GmRi\ t}$. production rate, and market price.

$$BR_t = \sum_{(i = 1 \text{ to } I)} B_{Ri\ t} \tag{5.73}$$

$$B_{Ri\ t} = \sum_{(c = 1 \text{ to } C)} B_{cRi\ t} \tag{5.74}$$

$$B_{cRi\ t} = BR_c \text{ X } P_{cRi\ t} \tag{5.75}$$

$$P_{cRi\ t} = PR_c \times W_{Ri\ t} \tag{5.76}$$

$$W_{Ri\ t} = \sum_{(m = 1 \text{ to } M)} W_{GmRi\ t} \tag{5.77}$$

where

BR_t = the benefit (revenue) obtained from the selling of all recovery materials produced from all recycling plants at time t.

$B_{Ri\ t}$ = the benefit (revenue) obtained from the selling of all recovery materials produced from recycling plant i at time t.

$B_{cRi\ t}$ = the benefit (revenue) obtained from the selling of recovery materials associated with each material (c) and recycling plant at any time t.

BR_c = the price of each recovery material

$P_{cRi\ t}$ = the amount of recovery material type c produced from recycling plant i at time t.

PR_c = the production rate associated with each recovery material from the recycling plant.

$W_{Ri\ t}$ = the total amount of SFLs sent to recycling plant i at time t.

$W_{GmRi\ t}$ = the amount of SFLs sent from generation node m to recycling plant i at time t.

With respect to the linkage of each model and the decision variables designed, a diagram depicting the conclusion of the model linkage was designed as shown in Figure 5.2.

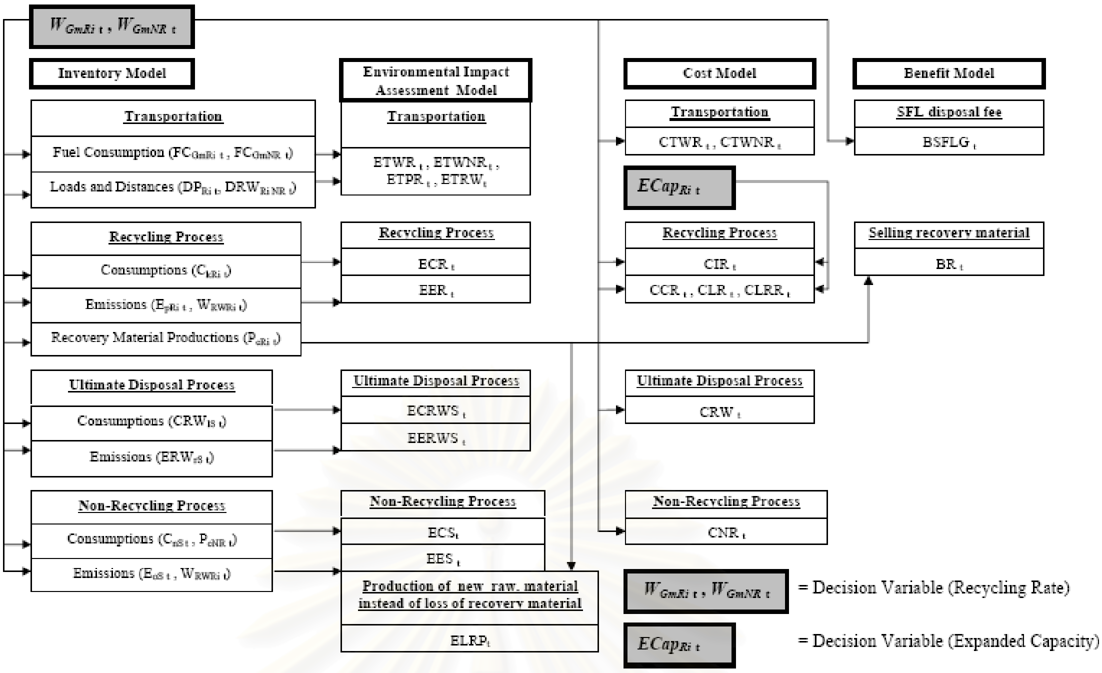


Figure 5.2 A diagram showing the linkage of each model and the decision variables

5.6 A decision making model for the recycling of waste

In this study, a decision-making model was formulated for the minimization of a problem, in which case, the objective was to minimize environmental impacts subject to cost-benefit constraints. The decision variables were the recycling rates, optimal added capacity for each recycling plant each year, and associated recycling plant locations.

The cost model exhibited capital cost savings which arose from the economies of scale in construction of the recycling plants. The model explored the trade-off between the economies of scale and the time-cost of early construction of recycling plants, as well as, the operating and maintenance costs for future demand on capacities.

Using the model formulation of the environmental impact assessment and costs and benefits analysis, developed in section 5.3 to 5.5, an integrated model for selecting the optimal recycling policy was designed as follows:

Objective function

Minimize TE_t (5.78)

Constraints

$\Sigma_{(t = 1 \text{ to } T)} \beta_t(TC_t-TB_t) \leq 0$ (5.79)

$\beta_t = [(1+f)/(1+r)]^{t-1}$ (5.80)

where

TE_t = the total environmental impact generated by the disposal of SFLs at time t.

TC_t = the total cost incurred from the disposal of SFLs at time t.

TB_t = the total benefit obtained from the disposal of SFLs at time t.

β_t = the discount factor, accounts for the inflation rate, f, and the nominal interest rate, r .

NPV = the net present value of the total cost-benefit each year

TNPV = the total net present value of the total cost-benefit (sum of all time t).

Total environmental impact generated by the disposal of SFLs at time t (TE_t):

$TE_t= ETWR_t+ETWNR_t+ECR_t+EER_t+ETPR_t+ETRW_t+ECRWS_t+EERWS_t+ECS_t+EES_t+ELRP_t$. (5.81)

Total cost incurred from the disposal of SFLs at time t (TC_t):

$TC_t = CTWR_t+ CCR_t+CLR_t+CIR_t+ CLLR_t+ CTWNR_t +CRW_t+CNR_t$. (5.82)

Total benefits obtained from the disposal of SFLs at time t (TB_t):

$TB_t = BR_t+BSFLG_t$. (5.83)

Net present value of the total cost minus the total benefit at each time t:

$NPV = \beta_t (TC_t-TB_t)$ (5.84)

Total net present value of the total cost minus the total benefit (summation of all time t):

$TNPV = \Sigma_{(t = 1 \text{ to } T)} \beta_t (TC_t-TB_t)$ (5.85)

Model complexity

Here the complexity of the problem arose from the number of planning horizon years, SFL generation node, recycling plants, and non-recycling plants.

Planning horizon (T) = 20
Number of SFL generation node (M) = 6
Number of hypothetical recycling plants (I) = 2
Number of Non-recycling plants (NR) = 1

Therefore, the complexity of the problem included:

Number of decision variables (d) = 400
of the amount of SFLs for recycling
or non-recycling at each node ($W_{GmRi\,t}$, $W_{GmNR\,t}$) = M × T × (I+NR) = 360
of the capacity variables ($ECap_{Ri\,t}$) = I × T = 40

Therefore, the study included a total of 400 decision variables. The model was solved using a commercial solver, Frontline Solver Program (more details on the solver are provided in appendix A).

5.7 The model input

For the model run, it was necessary to collect and explore six types of input data which are described as follows:

a) The main required input data for the SFL recycling network in the case study areas

For the general applications, several parameters of the recycling network were designed as free input. These inputs were categorized into three parts. The first part included general information on the number of planning years, number of recycling, number of recovery materials, and number of environmental impact groups. The second part involved those related to the recycling processes which include numbers of the various kinds of consumed materials and energy, and the emitted pollutants. The last was relevant to the non-recycling process. The inputs in this part were similar to those of the second part.

Table 5.1The main input data for the SFL study model

Planning years, T	20
Number of Generation node, M	6
Number of Hypotetical Recycling Plants, I	2
Number of kinds of recovery material, C	1
Number of kinds of environmental impacts, J	10
Recycling process	
Disassembly of waste	
Number of kinds of consumed materials & energy, K	3
Number of kinds of emitted pollutants, P	3
Ultimate disposal of residue waste (stabilization process) from the diassembly process	
Number of kinds of consumed materials&energy, L	4
Number of kinds of emitted pollutants, R	2
Non-recycling process	
The stabilization & solidification processes before entering a landfill	
Number of kinds of consumed materials & energy, N	4
Number of kinds of emitted pollutants, O	2

b) The inventory data

As mentioned earlier, the recycling and disposal processes, as well as the transportation processes generally consumed both materials and energy. The amounts of these consumptions depended on technologies specified for recycling and disposal. Unfortunately, the existing data sources of these data were not available for a regional recycling plant setting. The current existing data sources were only available in private firms. For these reasons, data on the consumption of material and energy, as well as the emissions employed in this study were collected from all industrial firms in which SFL management processes were in place. These data were shown in Table 5.2.

Additional data on fuel consumption factors utilized in estimating inventory that arose during the transportation processes was obtained from the study of the ETHS (ETH-ESU, 1996). The study suggested that the fuel consumption for a van is 0.000191 Liter/Kg.Km.

Table 5.2 Consumption and emission factors

Processes (Activities)	Kind of Comsumption/Emission	Units	Rate
Non-recycling process (Stabilization and solidification process)	**Comsumption**		
	Electricity use	kWh / SFL	0.0051
	Sodium sulfide use	kg / SFL	0.0140
	Cement use	kg / SFL	0.20
	Water use	m^3 / SFL	0.00020
	Loss of recovered glass (= new glass use)	kg / SFL	0.172
	Emission		
	Generated solid waste	kg / SFL	0.414
	Mercury vapor emission	kg / SFL	4.46E-08
Inventory data	Inventory data	Inventory data	Inventory data
	Electricity use	kWh / SFL	0.0029
	Water use	m^3 / SFL	0.00018
	Natural gas use	m^3 / SFL	0.000046
	Emission		
	Cullet	kg / SFL	0.17
	Residual solid waste	kg / SFL	0.028
	Mercury vapor emission	kg / SFL	4.38E-08
	Mercury in water emission	kg / SFL	7.36E-10
	Comsumption		
	Electricity use	kWh / SFL	0.00071
	Water use	m^3 / SFL	0.000028
	Sodium sulfide use	kg / SFL	0.0019
	Cement use	kg / SFL	0.028
	Emission		
	Generated solid waste	kg / SFL	0.057

Source: Philips Electronic (Thailand) Co., Ltd., 2004, and Genco Company Limited, 2006.

c) The environmental impact assessment data

The environmental impact assessment data was used to formulate the objective function of the study model. After inventory analyses were conducted using inventory models, the amounts of each inventory in the concerned processes were explored. These inventories, such as materials and energies including released pollutants and released products, generate environmental impacts.

In this study, the Eco-indicator method was used to assess the environmental impacts. This study also calculated and converted the environmental impacts into a single score unit. Therefore, the input data required in this part was composed of the characterization factor, damage assessment factor, normalization factor and weighing factor. Environmental impact assessment data regarding characterization were shown in Tables 5.3 and 5.4.

The environmental impact factors which arose from transportation activities were shown in Table 5.4.

As was shown in Table 5.3 and Table 5.4, these characterization factors were used to change each inventory of materials and energy consumed, including pollutants that were emitted from the SFL disposal process, into ten kinds of environmental impacts in different units. To convert the environmental impacts into a single score unit using the Eco-indicator 99 method, individualist version, the damage assessment, normalization, and weighing factors were all required.

These factors were collected from the database in the Simapro Demo Version 6 program in the part of the impact assessment methods, namely the Eco-indicator 99 (I) V2.1 as was shown in Tables 5.5 and 5.6.

Table 5.3 Environmental impact data for both the material and energy productions and the pollutant emissions.

Input/output of SFL disposal process	Characterization factor (Environmental impact factor)										References.
	Carcinogens (Daly/unit[a])	Resp. organics (Daly/unit[a])	Resp. inorganics (Daly/unit[a])	Climate change (Daly/unit[a])	Radiation (Daly/unit[a])	Ozone layer (Daly/unit[a])	Ecotoxicity (PAF*m^2yr/unit[a])	Acidification/ Eutrophication (PDF*m^2yr/unit[a])	Land use (PDF*m^2yr/unit[a])	Minerals (MJ surplus/unit[a])	
Electricity (kWh)	9.10E-09	5.19E-11	3.14E-08	4.82E-08	0	3.18E-12	6.02E-03	3.29E-03	0	0	Calculated by using mix ratio of electricity production in Thailand provided by PRET project 2003. The fuel mix was composed of coal (33.46%), natural gas(62.21%), bunker oil (4.2%), diesel(0.12%) and using environmental impact database of each fuel from project BUWAL 250 (1996).
Sodium sulfide (kg)	6.45E-09	1.54E-09	3.96E-07	1.28E-07	2.96E-10	6.57E-10	0.0477	0.0163	0.00675	0.00246	Chemical inorganic ETH S of project ETH-ESU 1996 system process, Zurich, Switzerland.
Cement (kg)	1.78E-08	2.84E-10	6.56E-08	1.99E-07	1.43E-10	8.36E-11	0.00935	0.0134	0.0044	0.000741	Cement ETH S of project ETH-ESU 1996 system process, Zurich, Switzerland.
Water (m^3)	4E-12	9.51E-14	1.15E-11	5.51E-12	2.02E-14	2.66E-14	0.00000512	0.00000117	0.00000198	0.000000351	Water decarbonized ETH S of project ETH-ESU 1996 system process, Zurich, Switzerland.
Natural gas (m^3)	2.24E-10	3.24E-10	2.52E-09	1.02E-08	2.10E-12	4.56E-12	1.71E-03	1.07E-03	3.15E-04	9.01E-05	Raw natural gas NL S, raw natural gas the Netherlands, project ETH-ESU 1996 system process, Zurich, Switzerland.
New glass production instead of glass loss incurred from non-recycling glass (kg)	1.07E-11	5.24E-12	8.13E-10	4.33E-10	0	1.08E-12	6.87E-05	3.27E-05	0	7.04E-10	Glass(virgin) of project BUWAL 250
Generated solid waste (kg)	2.41E-12	2.64E-12	2.93E-10	1.11E-10	3.49E-14	6.27E-13	7.76E-06	3.73E-05	0.000853	1.26E-06	Waste (inert) to landfill S of project ETH-ESU 1996 system process, Zurich, Switzerland.
Mercury vapor emission (kg)	0.0001742	0	0	0	0	0	4.53E+02	0	0	0	Heavy metals, unspecified in the air (for carcinogens) and CAS number 007439-97-6 (for ecotoxicity) of Eco-indicator 99 method, individualist version.
Mercury emission to water (kg)	0	0	0	0	0	0	1.93E+02	0	0	0	CAS number 007439-97-6 (for ecotoxicity) of Eco-indicator 99 method, individualist version.

[a] unit in this case mean one unit of material and fuel inputted and the emitted pollutants including with generated solid wastes outputted from disposal process

Table 5.4 The environmental impact factor for the assessment of the transportation process

Kind of vehicle used for transportation in a case study area.	Characterization factor (Environmental impact factor)										References.
	Carcinogens (Daly/unit[a])	Resp. organics (Daly/unit[a])	Resp. inorganics (Daly/unit[a])	Climate change (Daly/unit[a])	Radiation (Daly/unit[a])	Ozone layer (Daly/unit[a])	Ecotoxicity (PAF*m^2yr/unit[a])	Acidification/ Eutrophication (PDF*m^2yr/unit[a])	Land use (PDF*m^2yr/unit[a])	Minerals (MJ surplus/unit[a])	
Transportation by delivery van capacity size of this van is less than 3.5 tons	4.43E-8	1.10E-8	2.88E-7	3.41E-7	3.46E-10	1.89E-9	0.294	0.0534	0.0247	0.0381	Referred from the study of ETH S for transportation by delivery van capacity size of this van is less than 3.5 tons

[a] unit in this case mean ton-km.

Table 5.5 The amount of damage assessment factor used for the model input data.

Category		Value	Unit
Damage category	Impact category		
Human Health	Carcinogens	1	Daly/Daly
	Resp. organics	1	Daly/Daly
	Resp. inorganics	1	Daly/Daly
	Climate change	1	Daly/Daly
	Radiation	1	Daly/Daly
	Ozone layer	1	Daly/Daly
Ecosystem quality	Ecotoxicity	0.1	PDF*m^2yr /PAF*m^2yr
	Acidification/ Eutrophication	1	PDF*m^2yr/ PDF*m^2yr
	Land use	1	PDF*m^2yr/ PDF*m^2yr
Resources	Minerals	1	MJ surplus/ MJ surplus

Source: PRe Consultants, SimaPro 6.0 demo version program, 2005.

Table 5.6 Normalization and Weighing factors as referred by the Europe 99 I/I

Damage category	Normalization	Weighting
Human Health	121	550
Ecosystem quality	2.22E-4	250
Resources	6.68E-3	200

Source: PRe Consultants, SimaPro 6.0 demo version program, 2005.

c) The cost data

The cost data included costs of transportation, materials and energy for the recycling and non-recycling processes. Similarly to the inventory data, the cost data for both recycling and non-recycling were obtained from private sectors as a result of data deficiency. The result of the cost data collection was shown in Table 5.7.

Table 5.7 The cost parameter data of the model

Cost Category		**Cost**	**Unit**
Transportation Cost	Fuel cost of transport of SFLs to recycling process	30	Baht/Liter
	Fuel cost of transport of SFLs to non-recycling process	30	Baht/Liter
Recycling process Cost	**Cost of all consumed raw mat. & energy**		
	-Water	10.95	Baht/m^3
	-Natural gas	9	Baht/m^3
	-Electricity	2.7781	Baht/KWh
	-Cost of disposal residue waste	7	Baht/Kg of residual waste
	-Labor & Maintenance Cost	1.18	Baht/SFL
	-Land Rent Cost	1,200,000	Baht/a unit of expansion capacity
	Investment cost		
	-Machine	1,860,000	Baht/a unit of expansion capacity
	-Construction facilities Cost	900,000	Baht/a unit of expansion capacity
Non-recycling process Cost	Total non-recycling cost	1.4	Baht/SFL

Source: Philips Electronic (Thailand) Co., Ltd., 2004, and Genco Company Limited, 2006.

d) The benefit data

Similarly to all the above data, the benefit data were collected from private companies. These data include the disposal fee and price of recovery materials, as was shown in Table 5.8.

Table 5.8 The benefit parameter data of the model

Benefit Category	Value	Unit
Money paid by waste generator for disposal of their waste	3	Baht/SFL
Selling recovery material (Cullet)	2	Baht/a kg of cullet

Source: CoCusi Coque (Thailand) Co., Ltd. Seminar document of pilot scale project for recycling spent fluorescent lamps in Thailand; 2004.

e) Data for calculation net present value (NPV)

In this study, the net present value of costs and benefits were obtained by using the inflation and interest rates available from 1998 to 2007, as was shown in Table 5.9.

Table 5.9 The inflation and interest rates

Category of data prepared for NPV calculation	Value	Reference
Inflation Rate	2.8	http://www.bot.or.th/BoThomepage/databank/EconData/EconFinance/tab77-1.asp
Discount Rate (Interest rate)	6.83	http://www.bangkokbank.com/Bangkok+Bank+Thai/Web+Services/Rates/Loan+Interest+Rates.htm

From Table 5.9, the available data on the inflation rates in the study areas were calculated averaging from the first month in 1998 until September 2007, as was shown in Table 5.10. Additionally, the interest rates were collected from the MLR of the commercial bank in the study areas.

Table 5.10 The statistics of the headline inflation rate in Thailand.

Year	Headline Inflation in Thailand												Average Inflation Rate of the year
	Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1998	8.6	8.9	9.5	10.1	10.2	10.7	10	7.6	7	5.9	4.7	4.3	8.1
1999	3.5	2.9	1.6	0.4	-0.5	-1.2	-1.1	-1.1	-0.8	-0.5	0	0.7	0.3
2000	0.5	0.9	1.1	1.2	1.7	2	2	2.2	2.3	1.7	1.7	1.3	1.6
2001	1.3	1.5	1.4	2.6	2.8	2.3	2.2	1.4	1.4	1.4	1	0.8	1.6
2002	0.8	0.3	0.6	0.4	0.1	0.2	0.1	0.3	0.4	1.4	1.2	1.6	0.7
2003	2.2	1.9	1.7	1.6	1.9	1.7	1.8	2.2	1.7	1.2	1.8	1.8	1.8
2004	1.2	2.2	2.3	2.5	2.4	3	3.1	3.1	3.6	3.5	3	2.9	2.7
2005	2.7	2.5	3.2	3.6	3.7	3.8	5.3	5.6	6	6.2	5.9	5.8	4.5
2006	5.9	5.6	5.7	6	6.2	5.9	4.4	3.8	2.7	2.8	3.5	3.5	4.7
2007	3	2.3	2	1.8	1.9	1.9	1.7	1.1	2.1	no data	no data	no data	2
												Average Value	**2.8**

Source: http://www.bot.or.th/BoThomepage/databank/EconData/EconFinance/tab77-1.asp

CHAPTER VI

RESULTS AND DISCUSSION

After the required model input data were obtained, as was shown in chapter V, these data were used for the computation of the results of the research in two parts.

In the first part, the data were used in the life cycle assessment of SFLs in Thailand at various rates of recycling. This was to investigate as a preliminary study of what would happen in an LCA of FLs if the rates of SFL recycling were varied. Of the related processes, the transportation activities were excluded and the SFL generated loads were disregarded. The inventory data and the amount of environmental impact that was discovered in this assessment were documented as per a unit of SFL only.

The second part regarded the decision making model results revealing the optimum recycling rate and capacity of the recycling plant per year. These results were shown to answer the research questions of what the optimum rates of recycling are, what the optimum capacity of each recycling plant is and where the location sites for the recycling plant expansions should be as was described in the following explanation.

6.1 The LCA of SFLs in Thailand at various rates of recycling.

This part of the results revealed the amount of the environmental impact burden incurred in the life cycle of an FL at various rates of SFL recycling in Thailand by using data obtained from chapter V. The functional unit is a long tube SFL (36 watts, 200 grams and 13,600 hours for mean time before failure). The scope of the study was to characterize and compare the environmental impact between specified recycling technology and the secure landfill as described in the previous section. At present, since all SFLs to be disposed of have to be transported to a landfill site, the system boundaries of the study were considered after the SFLs arrived at the site. The activities included in the system boundaries were mainly both recycling and non-recycling processes: stabilization and solidification of the SFLs before the landfill. Various rates of the recycling of SFLs sent to recycling and non-recycling processes were studied. The intermittent activities, such as raw material production and energy used in recycling, non-recycling and all other related processes, were taken into account for environmental impact calculation.

Transportation and other activities in the life cycle of an FL were excluded. The considered system boundaries were shown in Figure 12

SFLs were separated into either recycling or the safe disposal of non-recycling materials. Rates of recycling in this study were varied as 100%, 80%, 60%, 40%, 20% and 0% (100% landfill), respectively. For recycling, the activities started at the beginning of the disassembly process (at the recycling plants) and terminated at the disposal process of residual waste in the disassembly process. The rest of the SFLs that were not put through the recycling process would be sent to safe disposal sites (a non-recycling process). Thus, the activities started at the landfill sites where SFLs were stabilized and solidified before being secured. Raw materials and energy production considered in this study were cement, water, sodium sulfide, glass and electricity production as well as natural gas extraction. The recovered material was glass cullet. The unrecovered cullet would be compensated by with the new glass production. Main emissions from these processes were solid waste and mercury. Inventory analyses (ISO, 1991) were conducted to identify and quantify inputs and outputs (raw material use, energy use, solid waste and mercury emitted to the air and water) from each related unit process as was shown in Figure 6.1.

From the inventory data in chapter V, the results included the amount of inputs and outputs per an SFL at 100% recycling and 100% non-recycling. To calculate inputs type i and outputs type i per an SFL with other recycling rates the following equation 89 was used:

$$Mi = RMi\,(R) + NRMi\,(1-R) \qquad (6.1)$$

where

Mi = The amount of inputs type i or the amount of outputs type i at recycling rate R.

R = Rate of recycling (e.g. equal to 0.2 for 20% recycling, 0.6 for 60% recycling).

RMi = The amount of inputs type i and the amount of outputs type i per an SFL at 100% recycling.

NRMi = The amount of inputs type i and the amount of outputs type i per an SFL at 100% non-recycling.

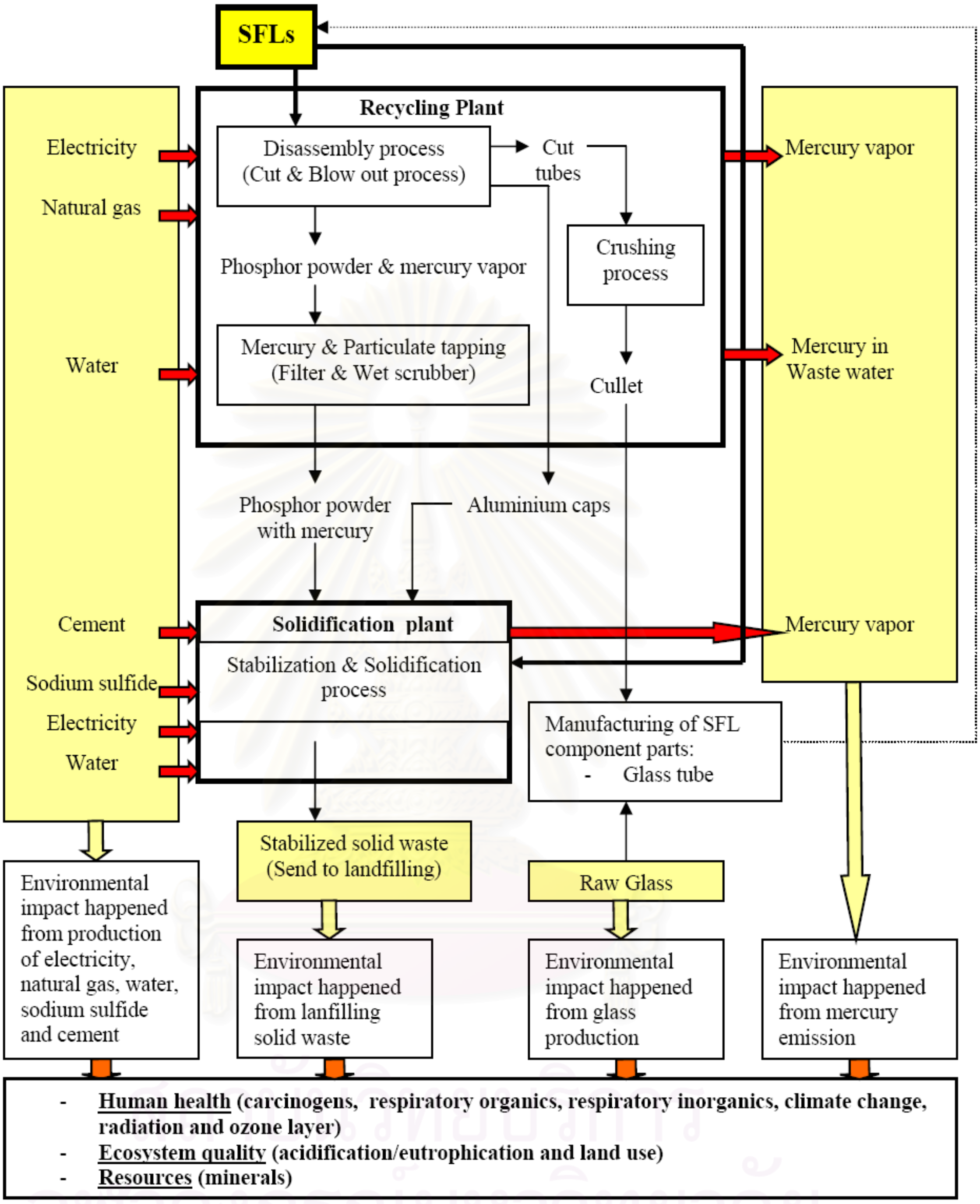


Figure 6.1 The system boundaries of the SFLs disposal alternatives

By using the collected data, environmental impact potentials (ISO, 2000) were calculated using an electronic spreadsheet with the assistance of information from the Simapro 6.0 database. The Eco-Indicator 99 (1) V2.1 was selected to assess the impacts which were classified into three main groups: human health, ecosystem quality, and resource depletion. The first group concerning human health (unit: DALY= Disability adjusted life years; this means different disabilities caused by diseases are weighed), was composed of carcinogens, respiratory organics, respiratory inorganics, climate change, radiation and ozone layer. The second group concerning ecosystem quality (unit: PDF*m^2yr; PDF= Potentially Disappeared Fraction of plant species) was composed of ecotoxicity, acidification/eutrophication and land use. The last one concerning resource depletion (unit: MJ surplus energy, additional energy requirement to compensate lower future ore grade) was focused on minerals. Environmental impact factors (characterization factor) from Simpro 6.0 database PRe Consultants, 2005, were reviewed as shown in chapter V.

With the exclusion of the damage assessment and normalization phases including the weighing factor phase, the environmental impact was calculated. The calculation included the amount of consumed materials and fuels per an SFL and that of emitted pollutants from the recycling process per an SFL multiplied by the environmental impact factor (characterization factor). The results showed the amount of environmental impact in the unit of each environmental impact category per a unit of SFL. The environmental assessment model used to calculate these impacts was shown in equation 90 below:

$$TE_k = EI_{ki} + EE_{ki} \tag{6.2}$$

$$EI_{ki} = CI_{ki} \times I_i \tag{6.3}$$

$$EE_{ki} = CE_{ki} \times E_i \tag{6.4}$$

Where:

TE_k = Total environmental impact of type k (per a SFL).

EI_{ki} = Environmental impact of type k generated from inputs (type i).

EE_{ki} = Environmental impact of type k generated from emissions (type i).

CI_{ki} = Characterization factor of impact type k per a unit of inputs.

CE_{ki} = Characterization factor of impact type k per a unit of emissions.

I_i = The amount of material and energy type i (per an SFL) inputted to the relevant processes.

E_i = The amount of emission type i (per an SFL) outputted from the relevant processes.

6.1.1 The results of the inventory analysis

The quantified inputs and outputs for disposing of one SFL at the end of its life at various recycling rates (raw material use, energy use, solid waste generation, as well as emissions to air and water) were calculated and the results were shown in Table 6.1. Total inputs and outputs of all activities were shown in Figure 6.2 and Figure 6.3, respectively.

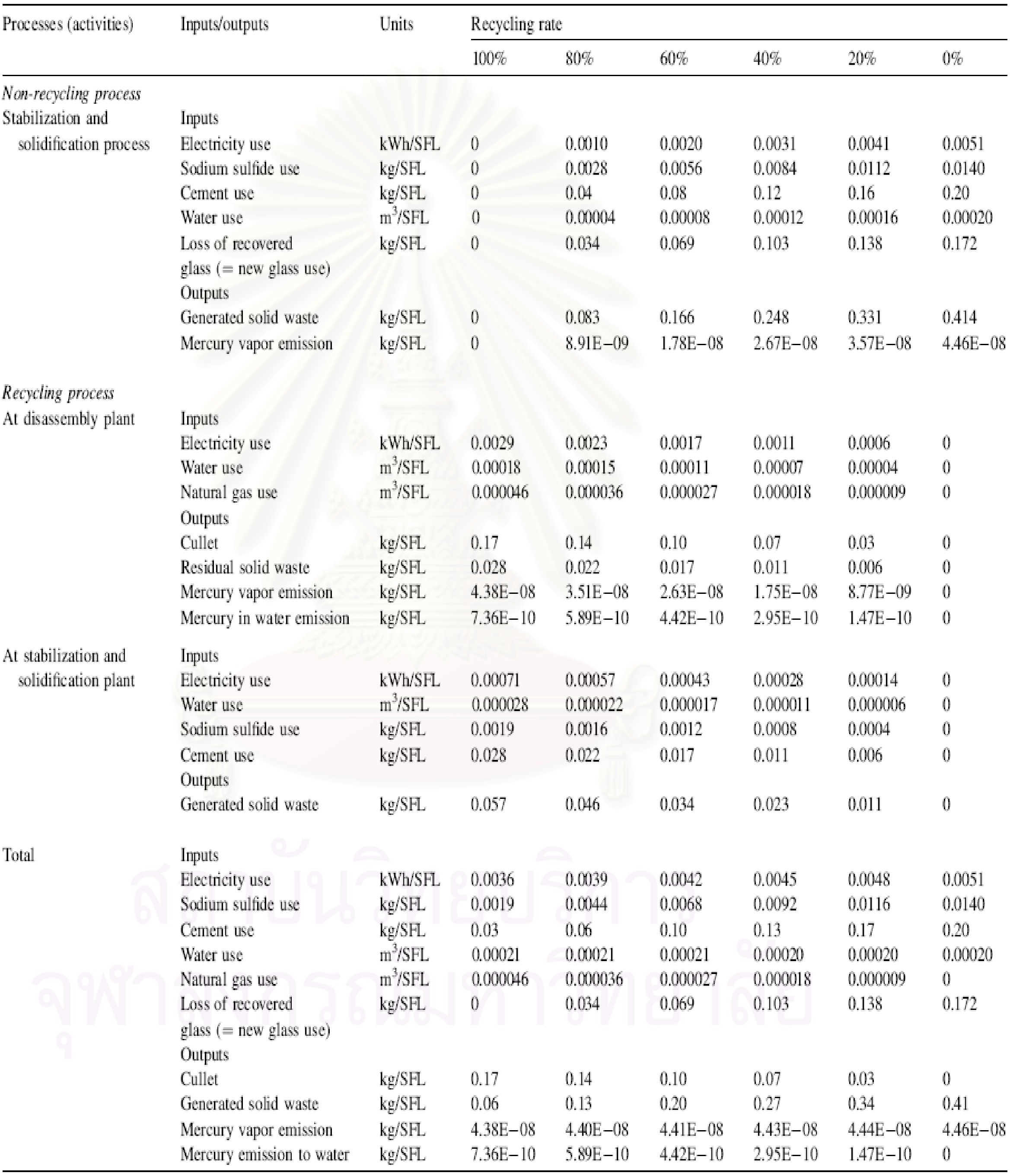
Figure 6.2 showed a linear relationship among the various inputs with the reduction of the recycling rate from 100 % to 0%. The amount of electricity consumption increased from 0.0036 to 0.0051 kWh/ SFL. The amount of sodium sulfide, cement and new glass also increased from 0.0019, 0.03, and 0 kg/SFL to 0.014, 0.20, and 0.172 kg/SFL, respectively. On the contrary, the amount of water and natural gas consumption decreased from 0.00021 and 0.000046 m^3/SFL to 0.0002 and 0 m^3/SFL, respectively.

Figure 6.3 showed the outputs and emissions from each of the related processes with respect to the change in recycling rates. All plots also showed a linear relationship between the process outputs and the rates of recycling. The amount of generated cullet was prominently reduced from 0.17 to 0 kg/SFL when the rate of recycling was reduced. On the contrary, generated solid waste and mercury vapor emission decreased and the emission of mercury to water also decreased from 7.36E-10 to 0 kg/SFL when the rate of recycling was increased.

From Table 6.1, when the total amount of the consumed materials and energy in the SFL disposal system were compared between 100% recycling (known as recycling) and 0% recycling (known as non-recycling), the results here indicated and confirmed that the recycling process consumes less material and energy than non-recycling. The results here also indicated and confirmed that recycling gives the advantage over non-recycling. It helped reduce the amount of consumed materials and energy in the SFL disposal system. For instance, less amounts of electricity, sodium sulfide, and cement were required for recycling than for non-recycling by about 1.42, 7.36 and 6.67 times, respectively. Moreover, the amount of new glass consumption for the non-recycling process was about 0.172 kg/SFL more. The water consumption in each approach was comparatively the same.

When considering the products and pollutant emissions from both recycling and non-recycling, the amount of cullet generated from recycling process was 0.17 kg/SFL. This implied that 0.17 kg of glass/SFL would be reduced from the resource extraction. It was also shown that recycling generates less amount of mercury vapor than non-recycling. The reason for this was that the existing recycling technology has a wet scrubber for reducing mercury vapor released from the disassembly process before emitting into the ambient air. Consequently, the amount of mercury released into the ambient air did not exceeded the emission standard. In addition, the analysis showed that non-recycling generates 0.35 kg more of solid waste/SFL than recycling.

Table 6.1 The quantified inputs and outputs for each activity to dispose of one SFL (0.2 kg) at the end of its life at various recycling rates



Processes (activities)	Inputs/outputs	Units	Recycling rate					
			100%	80%	60%	40%	20%	0%
Non-recycling process								
Stabilization and solidification process	Inputs							
	Electricity use	kWh/SFL	0	0.0010	0.0020	0.0031	0.0041	0.0051
	Sodium sulfide use	kg/SFL	0	0.0028	0.0056	0.0084	0.0112	0.0140
	Cement use	kg/SFL	0	0.04	0.08	0.12	0.16	0.20
	Water use	m^3/SFL	0	0.00004	0.00008	0.00012	0.00016	0.00020
	Loss of recovered glass (= new glass use)	kg/SFL	0	0.034	0.069	0.103	0.138	0.172
	Outputs							
	Generated solid waste	kg/SFL	0	0.083	0.166	0.248	0.331	0.414
	Mercury vapor emission	kg/SFL	0	8.91E−09	1.78E−08	2.67E−08	3.57E−08	4.46E−08
Recycling process								
At disassembly plant	Inputs							
	Electricity use	kWh/SFL	0.0029	0.0023	0.0017	0.0011	0.0006	0
	Water use	m^3/SFL	0.00018	0.00015	0.00011	0.00007	0.00004	0
	Natural gas use	m^3/SFL	0.000046	0.000036	0.000027	0.000018	0.000009	0
	Outputs							
	Cullet	kg/SFL	0.17	0.14	0.10	0.07	0.03	0
	Residual solid waste	kg/SFL	0.028	0.022	0.017	0.011	0.006	0
	Mercury vapor emission	kg/SFL	4.38E−08	3.51E−08	2.63E−08	1.75E−08	8.77E−09	0
	Mercury in water emission	kg/SFL	7.36E−10	5.89E−10	4.42E−10	2.95E−10	1.47E−10	0
At stabilization and solidification plant	Inputs							
	Electricity use	kWh/SFL	0.00071	0.00057	0.00043	0.00028	0.00014	0
	Water use	m^3/SFL	0.000028	0.000022	0.000017	0.000011	0.000006	0
	Sodium sulfide use	kg/SFL	0.0019	0.0016	0.0012	0.0008	0.0004	0
	Cement use	kg/SFL	0.028	0.022	0.017	0.011	0.006	0
	Outputs							
	Generated solid waste	kg/SFL	0.057	0.046	0.034	0.023	0.011	0
Total	Inputs							
	Electricity use	kWh/SFL	0.0036	0.0039	0.0042	0.0045	0.0048	0.0051
	Sodium sulfide use	kg/SFL	0.0019	0.0044	0.0068	0.0092	0.0116	0.0140
	Cement use	kg/SFL	0.03	0.06	0.10	0.13	0.17	0.20
	Water use	m^3/SFL	0.00021	0.00021	0.00021	0.00020	0.00020	0.00020
	Natural gas use	m^3/SFL	0.000046	0.000036	0.000027	0.000018	0.000009	0
	Loss of recovered glass (= new glass use)	kg/SFL	0	0.034	0.069	0.103	0.138	0.172
	Outputs							
	Cullet	kg/SFL	0.17	0.14	0.10	0.07	0.03	0
	Generated solid waste	kg/SFL	0.06	0.13	0.20	0.27	0.34	0.41
	Mercury vapor emission	kg/SFL	4.38E−08	4.40E−08	4.41E−08	4.43E−08	4.44E−08	4.46E−08
	Mercury emission to water	kg/SFL	7.36E−10	5.89E−10	4.42E−10	2.95E−10	1.47E−10	0

Source: All data calculated by using equation 6.1

6.1.2 The result of the environmental impact assessment

. Figures 6.4 - 6.13 displayed the main contribution of each environmental impact. From Figures 6.4 - 6.13 the results showed that the main contributor to the environmental impacts was coming from cement production. It was responsible for more than 60% of the total contributions to the environmental impacts. Furthermore, it was observed that when the recycling rate was increased, the environmental impacts from each category were reduced. When the impacts from each category were considered, they were summarized as follows:

- **Carcinogens:** the total amount of carcinogens ranged from $5.47x10^{-10}$ to $3.71x10^{-9}$ Daly/SFL at various rates of recycling and tended to increase when the rates of recycling were reduced. The main sources of carcinogens primarily came from cement production (90-96%). The remaining contributions were due to electricity production, sodium sulfide production and mercury vapor emissions, respectively.
- **Respiratory organics:** the total amount of respiratory organics at various recycling rates was varied from $1.12x10^{-11}$ to $8.06x10^{-11}$ Daly/SFL. The cement production and sodium sulfide production were the main sources with contributions of 70% and 27%, respectively. The contribution from electricity production, solid waste landfill, and new glass production was less than 2%.
- **Respiratory inorganics:** the total amount of respiratory inorganics was varied from $2.72x10^{-09}$ to $1.91x10^{-08}$ Daly/SFL. The cement production and sodium sulfide production were the main sources with contributions of more than 67% and 28% respectively. Another contributor was electricity production. The contribution from solid waste landfill and new glass production accounted for less than 4%.
- **Climate change:** the total amount of climate change at various rates of recycling was about $5.95x10^{-09}$ to $4.20x10^{-08}$ Daly/SFL. Of this, more than 93% was from cement production. Others were sodium sulfide and electricity production, respectively.
- **Radiation:** the total amount of radiation was about $4.54x10^{-12}$ to $3.28x10^{-11}$ Daly/SFL and it tended to increase when the rate of recycling was reduced. Cement and sodium sulfide production were the main contributors with 87% and 13% contribution, respectively.

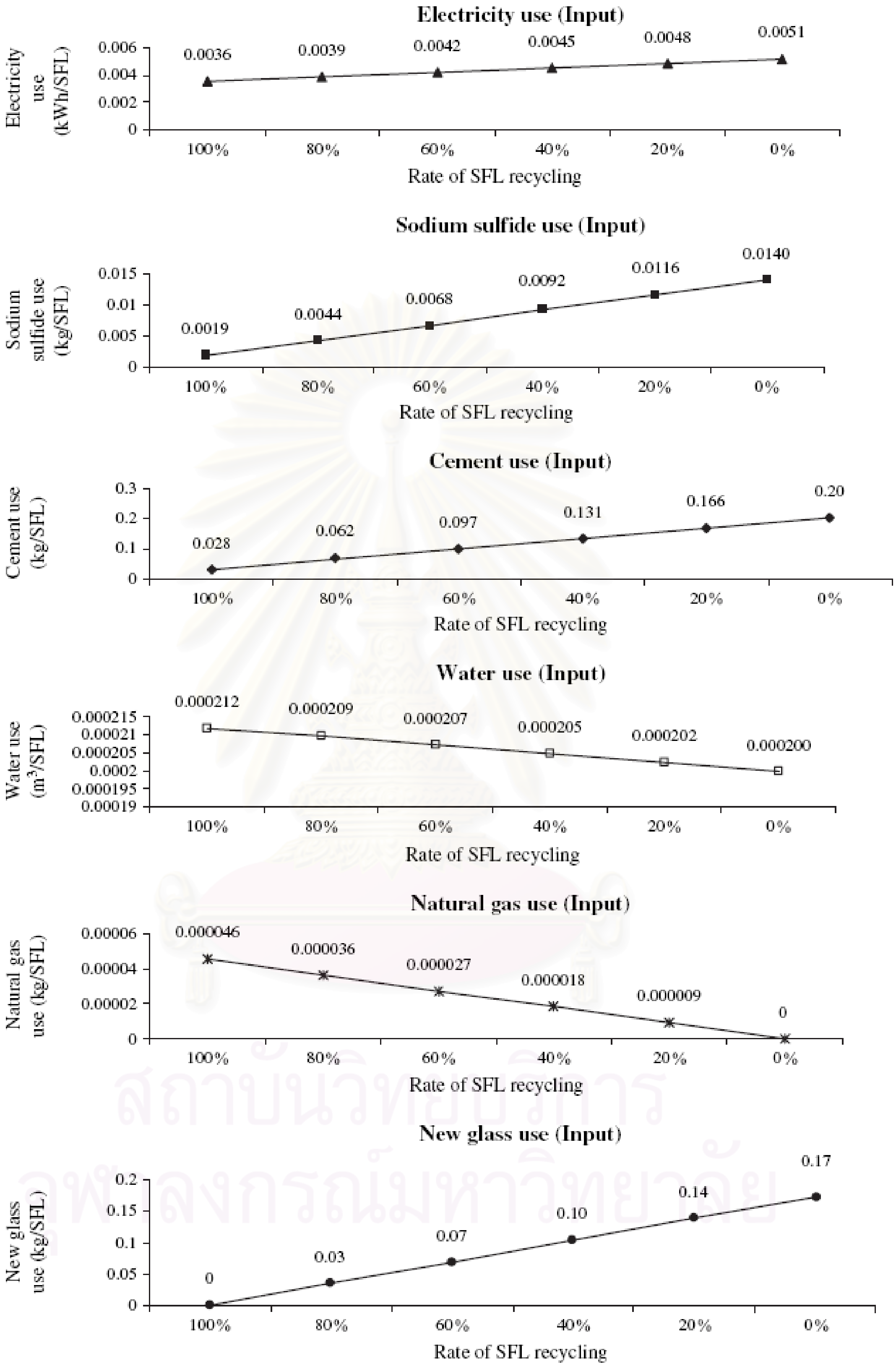


Figure 6.2 The inputs for each activity to dispose of one SFL (0.2 kg) at the end of its life at various recycling rates.

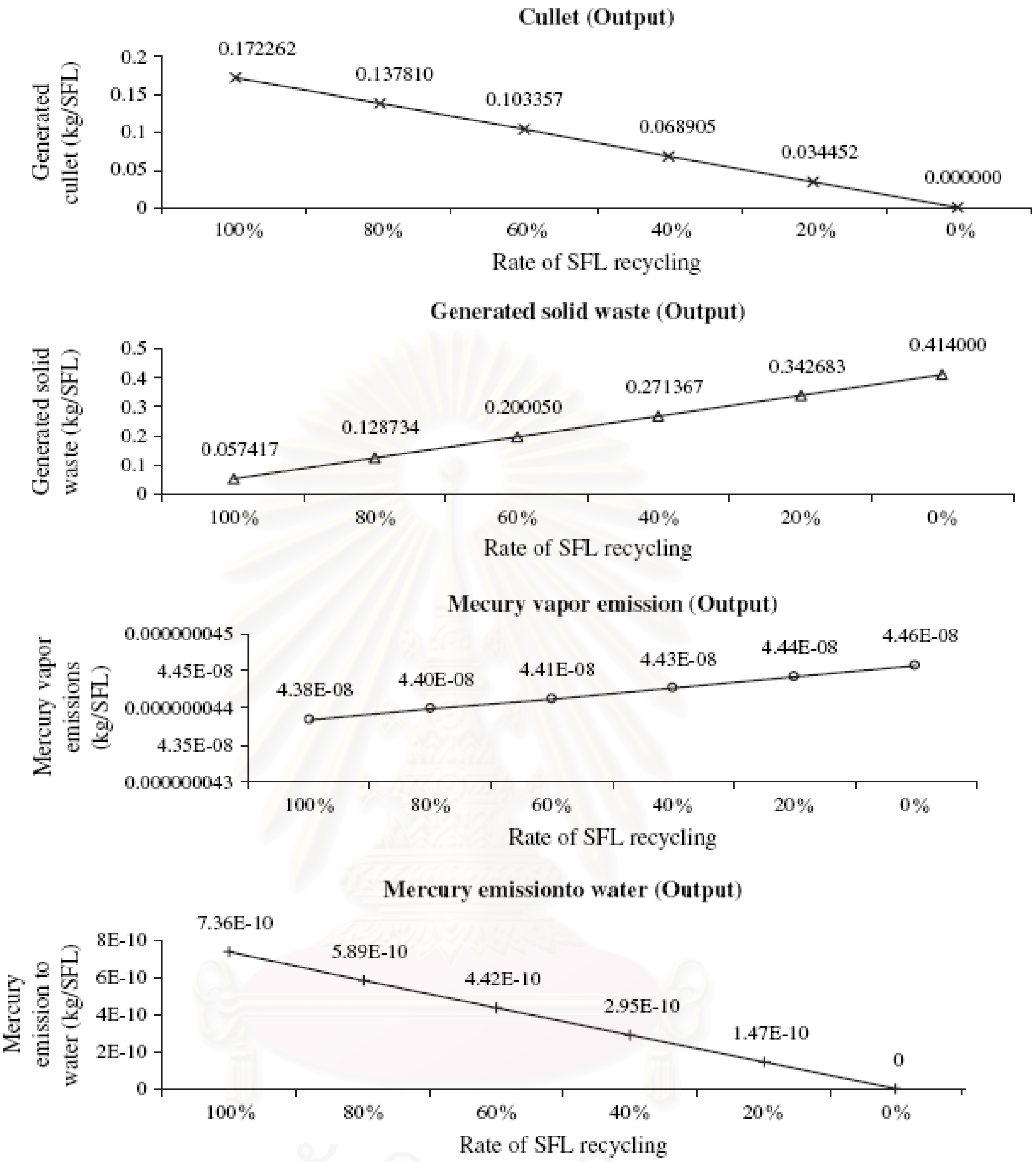


Figure 6.3 The outputs from each activity to dispose of one SFL (0.2 kg) at the end of its life at various recycling rates.

- **Ozone layer:** ozone depletion was primarily due to the cement production which contributed to 63%. Others were sodium sulfide production, landfill solid waste and new glass production which contributed to 35%, 1% and 1%, respectively. The total ozone layer depletion was increased from 3.64×10^{-12} to 2.64×10^{-11} Daly/SFL when the recycling rate was reduced.
- **Ecotoxicity:** the ecotoxicity was about 3.94×10^{-4} and increased to 2.60×10^{-3} PAF*m^{2}yr/SFL when the recycling rate was reduced**.** Main ecotoxicity sources

were the cement and sodium sulfide productions. Electricity production and mercury vapor emission from the disposal process contributed less than 5%.

- **Acidification/Eutrophication:** The main contributor was still cement production. Its contribution was about 90%, while sodium sulfide production contributed only 8%. Electricity production contributed less than 3% and solid waste landfill contributed 1%. The impact due to the total acidification/ eutrophication was 4.17×10^{-4} and increased to 2.95×10^{-03} PDF*m^{2}yr/SFL when the recycling rate was reduced**.**
- **Land use:** the impact due to total land use varied from 1.36×10^{-04} to 9.78×10^{-04} PDF*m^{2}yr/SFL when the recycling rate was reduced**.** Cement production was again the main contributor at about 90%. The remaining 10% was from sodium sulfide production.
- **Minerals:** the total amount of minerals varied from 2.75×10^{-05} to 1.98×10^{-04} PDF*m^{2}yr/SFL when the recycling rate was reduced**.** The main source of mineral depletion was from cement production which contributed to 75%. The rest was from sodium sulfide production and solid waste landfill which contributed up to 17% and 8%, respectively.

6.2 The decision making model output results

After this model was formulated on an Excel spreadsheet and all required data were inputted in the input interface, then, the Frontline Solver was used as a tool to find out the optimum solution of the case study areas. The outputs of the model were shown in this part. The main outputs of this decision making model for setting up the optimal SFL recycling policy were the amount of SFLs at each generation node that was sent to a recycling process, a non-recycling process, as well as, the optimum percentage recycling rate for each year. Also, the optimum capacities of each recycling plant for each year were required. All of these factors were used to answer the research questions about where and when recycling plants should be set up and expanded; how many units of expansion should there be; and what the percent of the SFL recycling rate should be each year. The objective of the model was that the total environmental impacts should be minimized and the net present value (NPV) of the total benefits should be more than the NPV of costs in terms of money.

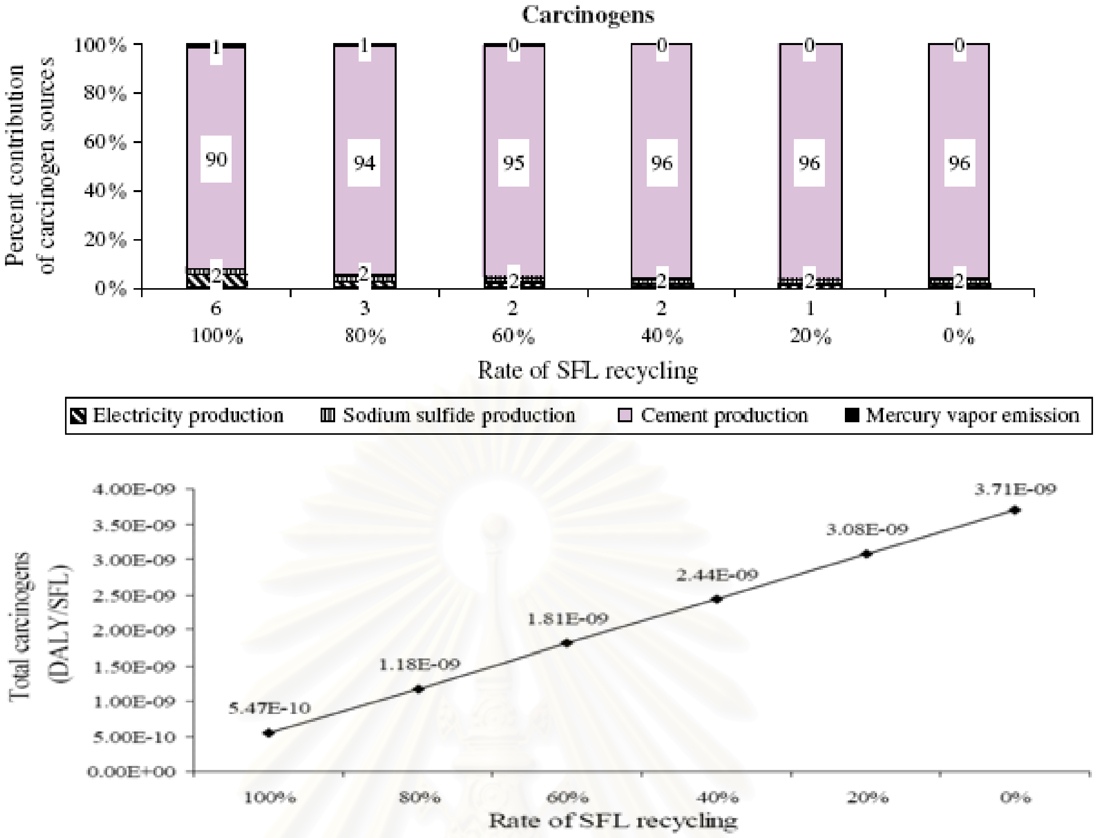


Figure 6.4 The percents of contributions from carcinogen sources and the total amount of carcinogens at various SFL recycling rates.

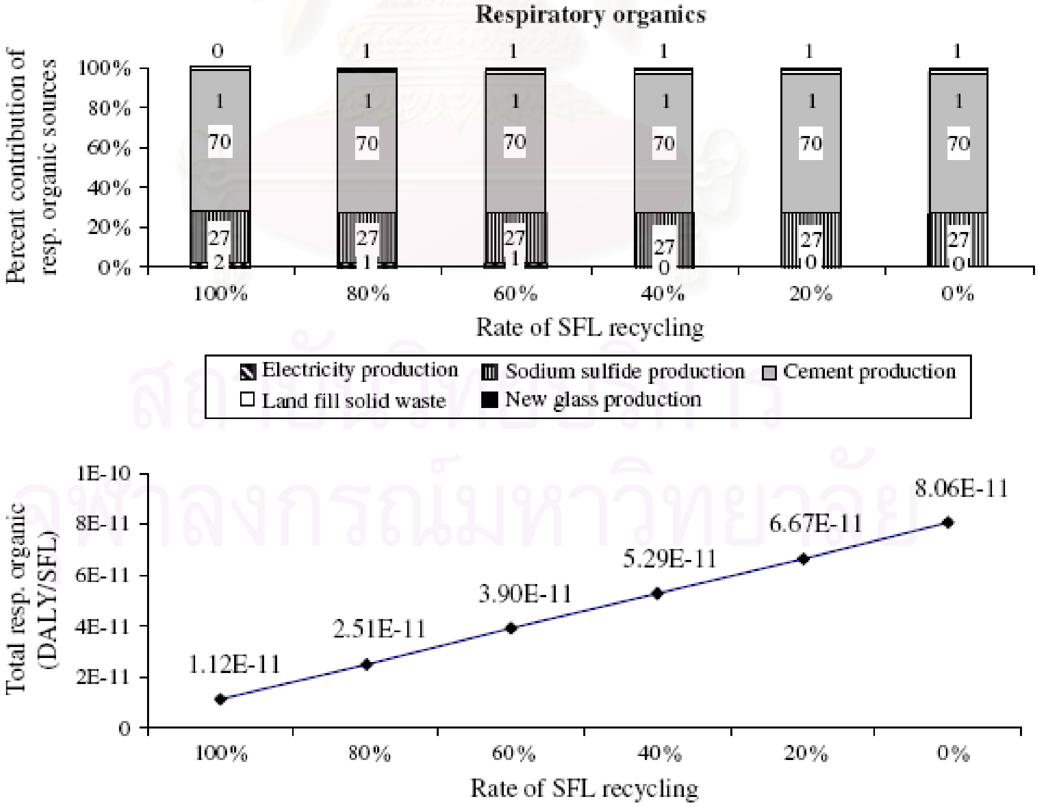


Figure 6.5 The percents of contributions from respiratory organic sources and the total amount of respiratory organics at various SFL recycling rates.

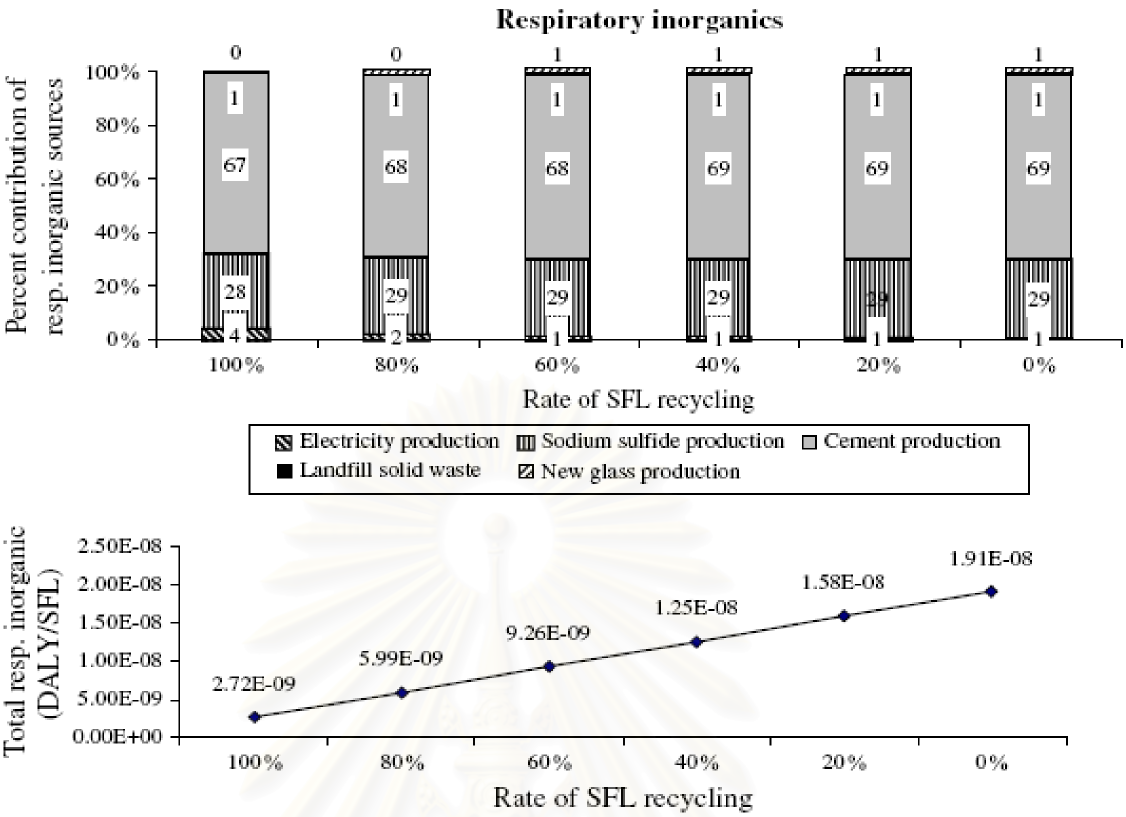


Figure 6.6 The percents of contributions from respiratory inorganic sources and the total amount of respiratory inorganics at various SFL recycling rates.

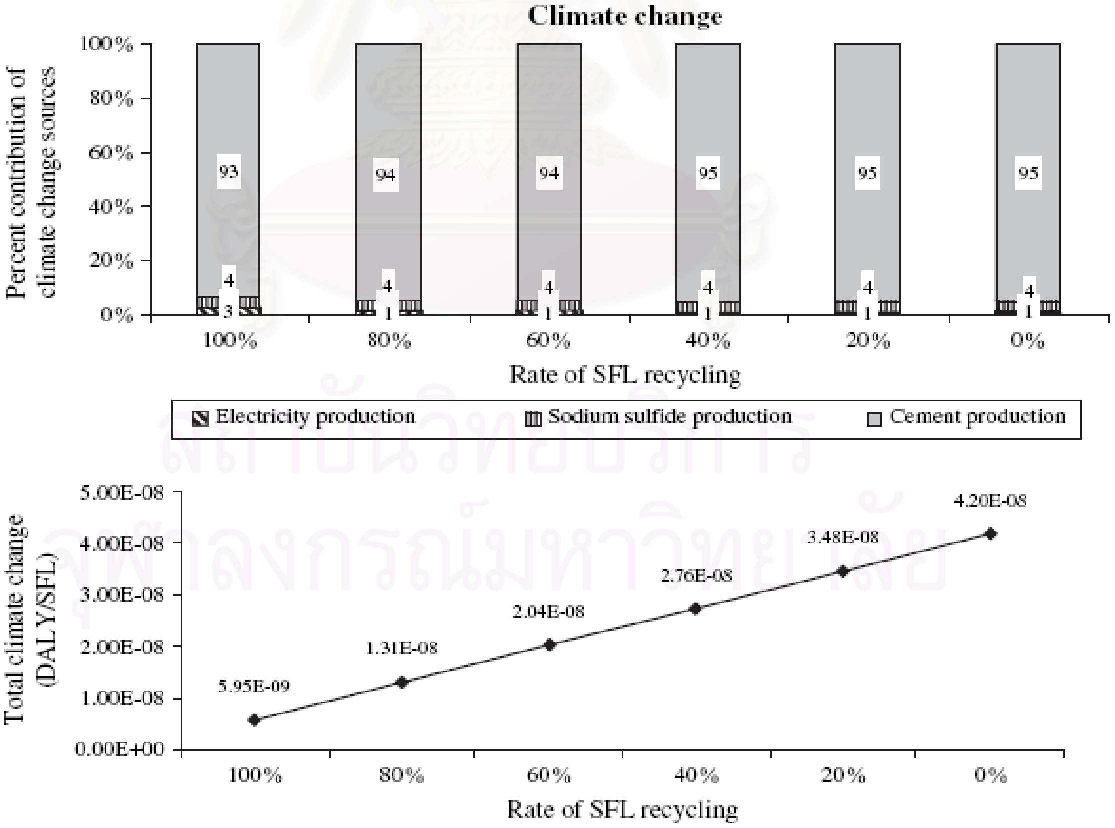


Figure 6.7 The percents of contributions from climate change sources and the total amount of climate change at various SFL recycling rates.

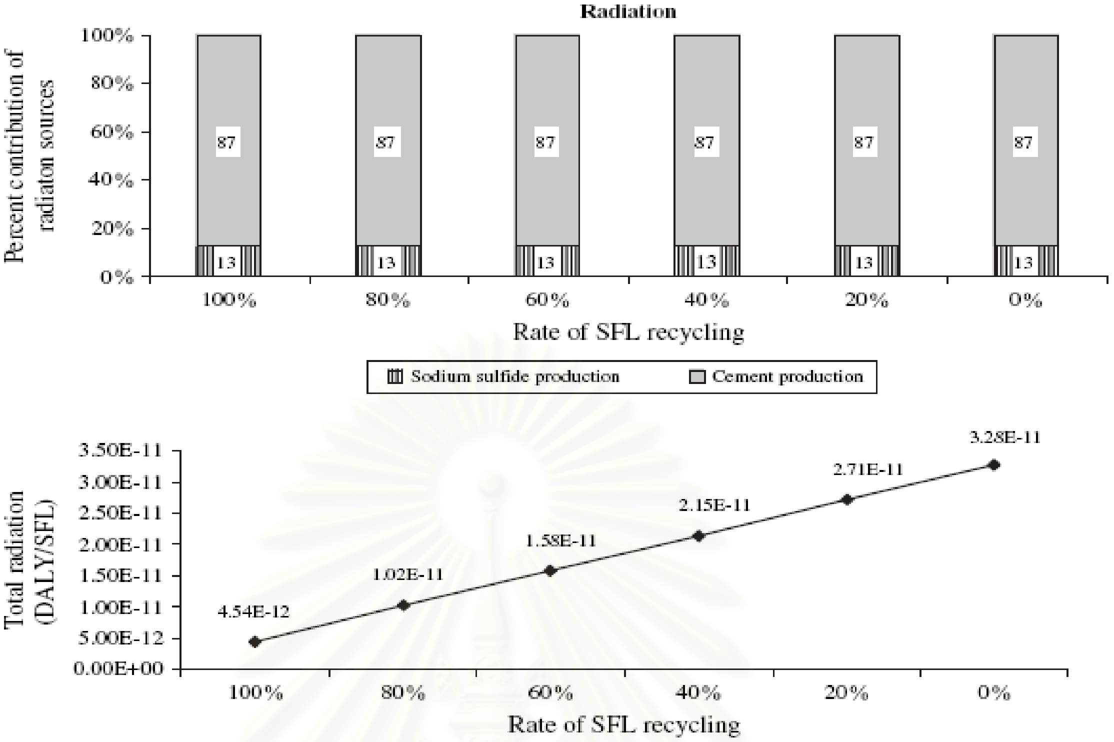


Figure 6.8 The percents of contributions from radiation sources and the total amount of radiation at various SFL recycling rates.

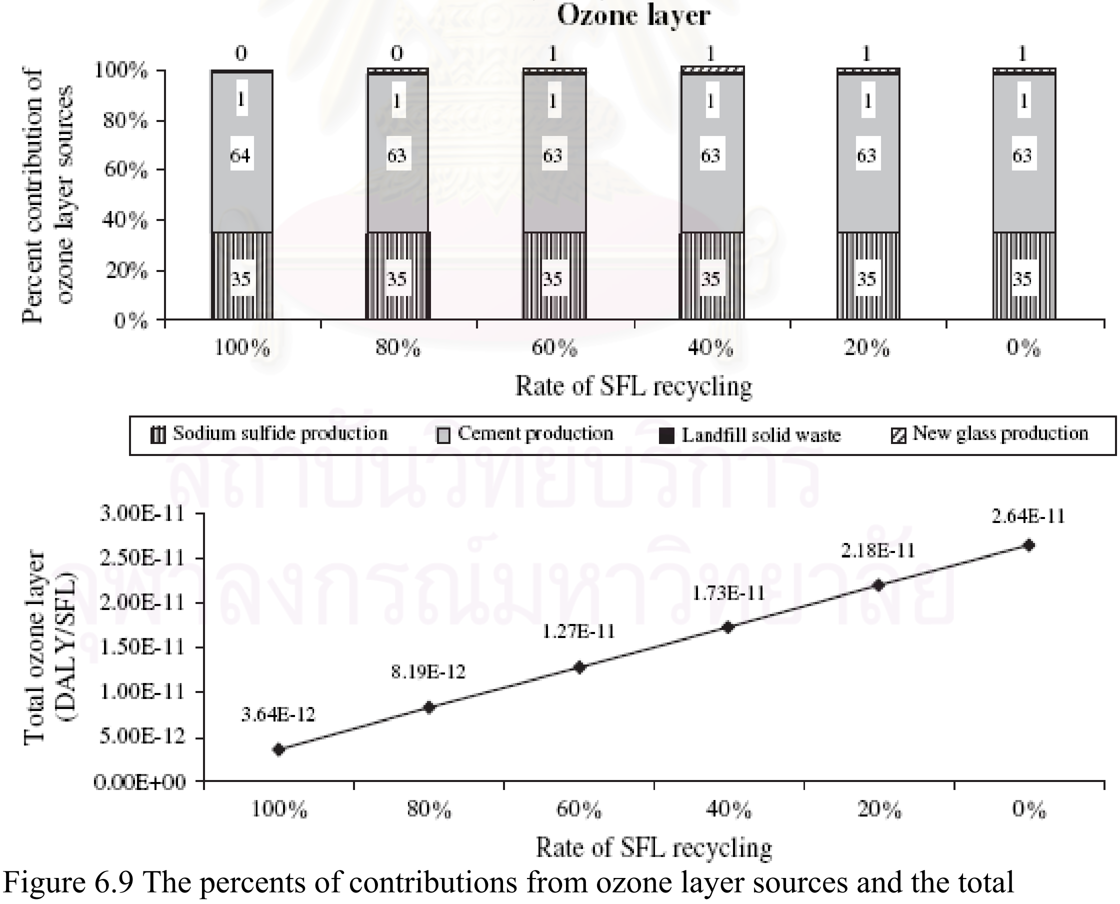


Figure 6.9 The percents of contributions from ozone layer sources and the total amount of ozone layer at various SFL recycling rates.

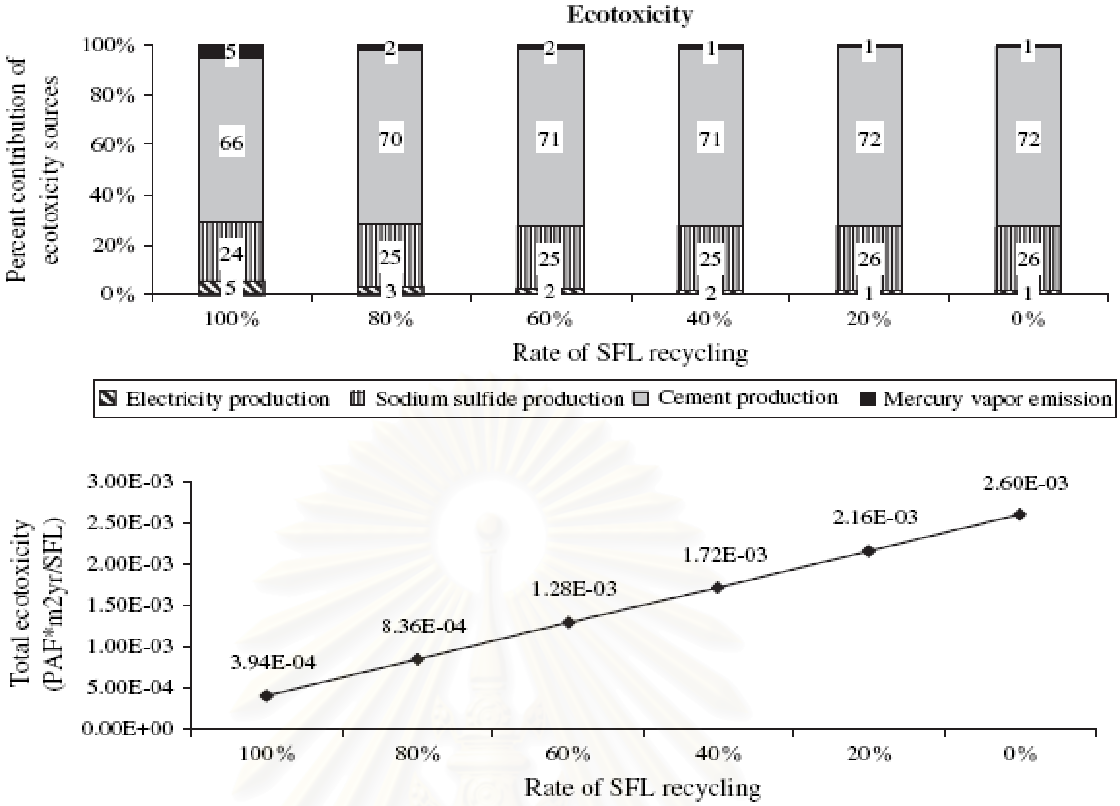


Figure 6.10 The percents of contributions from ecotoxicity sources and the total amount of ecotoxicity at various SFL recycling rates.

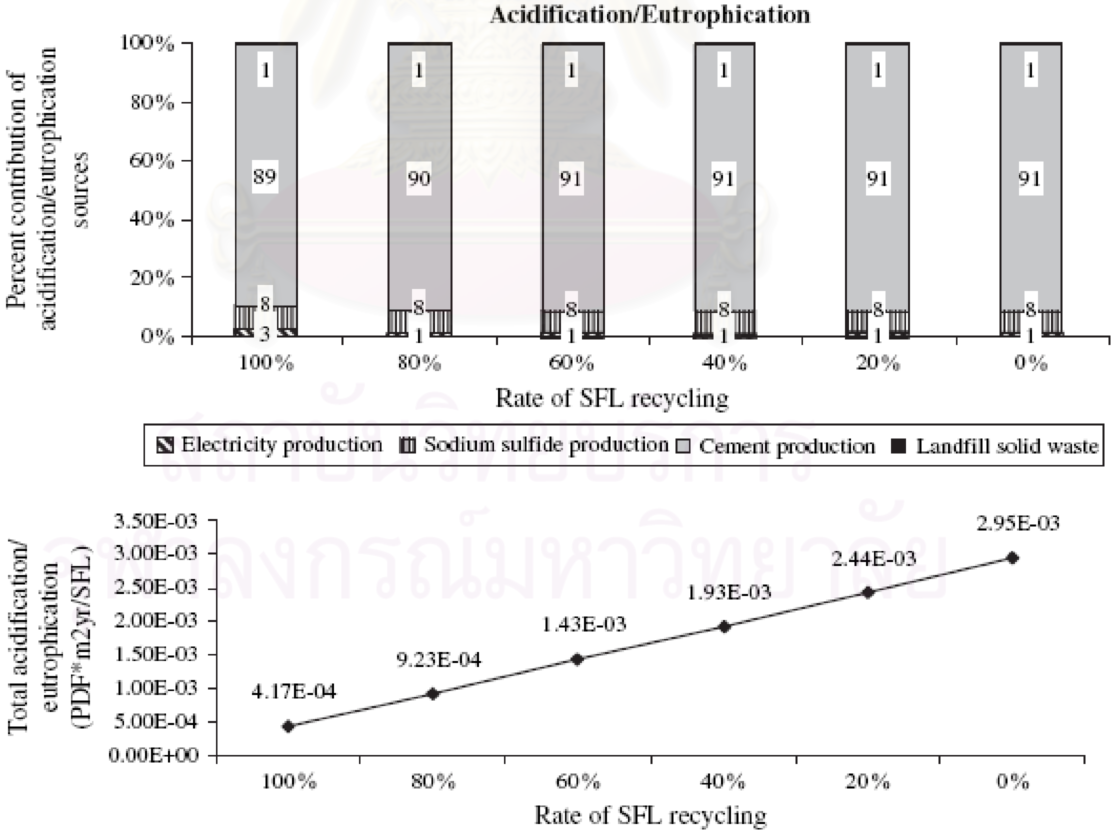


Figure 6.11 The percents of contributions from acidification/eutrophication sources and the total amount of acidification/eutrophication at various SFL recycling rates.

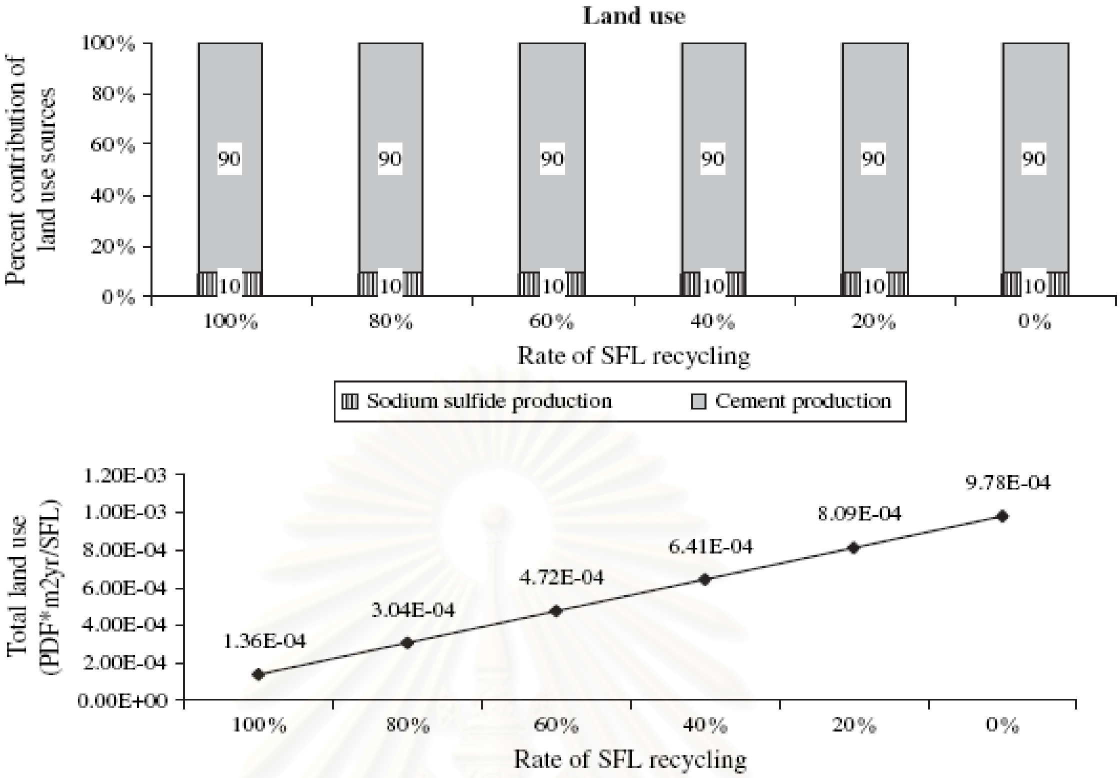


Figure 6.12 The percents of contributions from land use sources and the total amount of land use at various SFL recycling rates

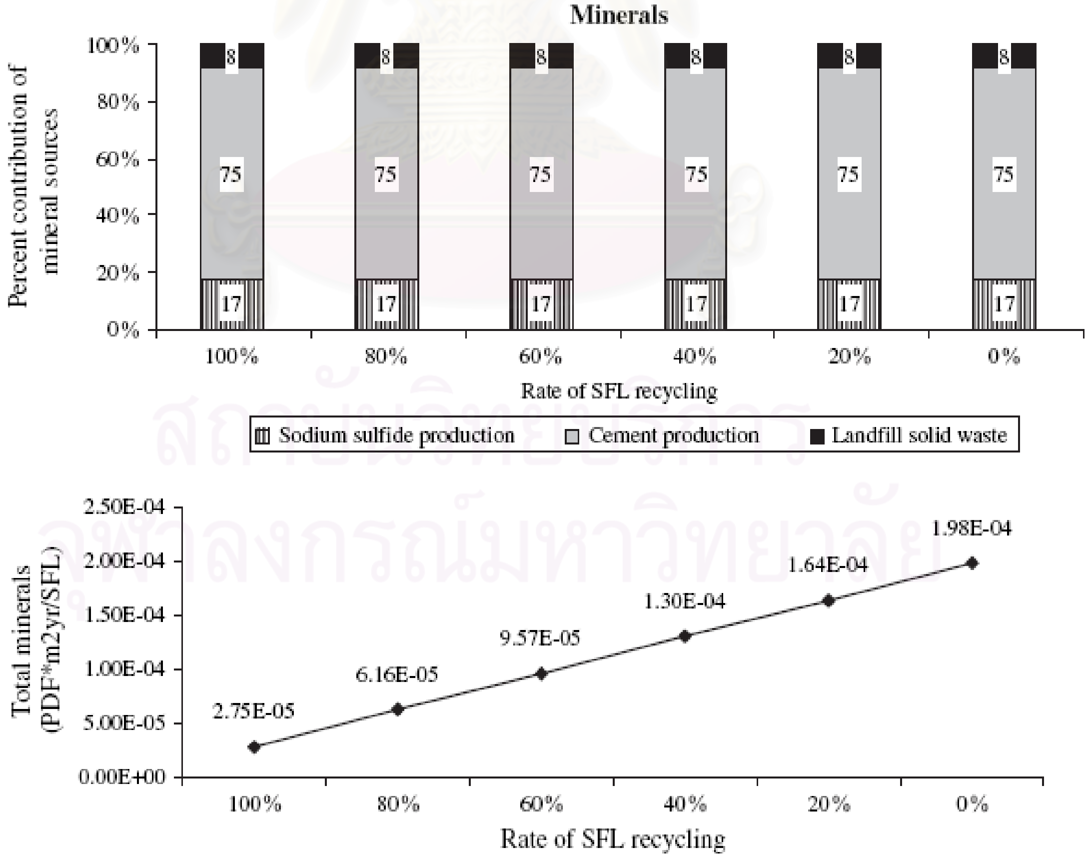


Figure 6.13 The percents of contributions from mineral sources and the total amount of minerals at various SFL recycling rates.

The amounts of SFLs generated at each generation node in the study areas per year.

After all required data were inputted into the model for the prediction of the amount of SFLs generated in the future; the amounts of SFLs for each year were predicted. Using the 2007 base-year data coupled with the percent growth rates as shown in Table 4.2, the resulting amounts of SFLs generated over the next 20 years were obtained as shown in Table 6.2.

Table 6.2 The amounts of SFLs generated at each generation node in the study areas per year

Year (A.D.)	**The amount of SFLs generated at each generation nodes in case study area in Thailand (lamps)**						
	Name of each generation node (province)						
	Bangkok	**Nakhonpathom**	**Nonthaburi**	**Pathumthani**	**Samutprakarn**	**Samutsakhon**	**Total**
2007	10,869,400	601,205	467,970	800,111	2,397,050	1,182,240	16,317,976
2008	11,298,540	641,418	488,194	800,443	2,531,100	1,278,120	17,037,815
2009	11,727,680	681,631	508,418	800,775	2,665,150	1,374,000	17,757,654
2010	12,156,820	721,844	528,642	801,108	2,799,200	1,469,880	18,477,494
2011	12,585,960	762,057	548,866	801,440	2,933,250	1,565,760	19,197,333
2012	13,015,100	802,270	569,090	801,772	3,067,300	1,661,640	19,917,172
2013	13,444,240	842,483	589,314	802,104	3,201,350	1,757,520	20,637,011
2014	13,873,380	882,696	609,538	802,436	3,335,400	1,853,400	21,356,850
2015	14,302,520	922,909	629,762	802,769	3,469,450	1,949,280	22,076,690
2016	14,731,660	963,122	649,986	803,101	3,603,500	2,045,160	22,796,529
2017	15,160,800	1,003,335	670,210	803,433	3,737,550	2,141,040	23,516,368
2018	15,589,940	1,043,548	690,434	803,765	3,871,600	2,236,920	24,236,207
2019	16,019,080	1,083,761	710,658	804,097	4,005,650	2,332,800	24,956,046
2020	16,448,220	1,123,974	730,882	804,430	4,139,700	2,428,680	25,675,886
2021	16,877,360	1,164,187	751,106	804,762	4,273,750	2,524,560	26,395,725
2022	17,306,500	1,204,400	771,330	805,094	4,407,800	2,620,440	27,115,564
2023	17,735,640	1,244,613	791,554	805,426	4,541,850	2,716,320	27,835,403
2024	18,164,780	1,284,826	811,778	805,758	4,675,900	2,812,200	28,555,242
2025	18,593,920	1,325,039	832,002	806,091	4,809,950	2,908,080	29,275,082
2026	19,023,060	1,365,252	852,226	806,423	4,944,000	3,003,960	29,994,921

Note: The base year data was obtained from Table 4.2

From Table 6.2, it was noted that the largest generation source of SFLs was Bangkok and the second was Samutprakarn Province. The smallest generation source was Nonthaburi. The initial total amount of SFLs generated in the study areas was 16,317,976 lamps per year and this amount tended to increase every year. The projected total amount of SFLs would approximately be 29,994,921 per year in the next 20 years.

Hypothetical recycling plants in the study areas and the optimum capacity expanded per year in the planning time.

As mentioned earlier, the study areas included Bangkok and the vicinities, which were Nakhonpathom, Nonthaburi, Pathumthani, Samutprakarn and Samutsakhon. Firstly, for the selection of sites of hypothetical recycling plants, it was necessary to consider not only the appropriateness of a transportation path but also the regulations enforced by the Department of Industry (DOI). As a result of these regulations, two locations for hypothetical recycling plants were selected. The first one was located in Samutprakarn province. The second was located at Pathumthani province. The other locations in the study areas did not meet the regulations.

To find out the optimum capacity expanded each year, the capacity's upper bound of the existing technology of recycling was inputted as that of the recycling technology used in this decision making model. It is presently 1.269 millions of SFLs a year. This amount was obtained from data collection at an existing plant in Samutprakarn in the study area. The optimum capacity of each recycling plant provided after running the model was shown in Table 6.3.

Table 6.3 The optimum capacity of each recycling plant at each year in the study area

Year	**The capacity of each recycling plant at each year**			
	Recycling Plant 1		**Recycling Plant 2**	
	Lamps	**Units**	**Lamps**	**Units**
2007	13,959,000	11	1,269,000	1
2008	1,269,000	1	1,269,000	1
2009	0	0	0	0
2010	1,269,000	1	0	0
2011	1,269,000	1	0	0
2012	2,538,000	2	0	0
2013	1,269,000	1	0	0
2014	1,269,000	1	0	0
2015	1,269,000	1	0	0
2016	2,538,000	2	0	0
2017	1,269,000	1	0	0
2018	1,269,000	1	0	0
2019	1,269,000	1	0	0
2020	2,538,000	2	0	0
2021	1,269,000	1	0	0
2022	1,269,000	1	0	0
2023	2,538,000	2	0	0
2024	1,269,000	1	0	0
2025	1,269,000	1	0	0
2026	1,269,000	1	0	0
Total	**41,877,000**	**33**	**2,538,000**	**2**

As shown in Table 6.3, the demand for additional recycling plant capacity varied by year and location. The initial demand of recycling capacity at Recycling Plant 1 was 11 units while the maximum capacity obtained was 13,959,000. The required capacity expansion tended to increase every year over the 20-year planning horizon, yielding only in the third year which showed that expansion at Recycling Plant 1 was not needed. In consideration of Recycling Plant 2, the initial demand for additional capacity was one unit and the second-year showed an increment of recycling plant capacity at one unit as well. After that, from the third year until the end of the planning horizon, an increased capacity at Recycling Plant 2 was not necessary. In conclusion, the total requirement of the recycling plant capacity at Recycling Plant 1 was 33 units over the planning horizon. This could serve to recycle a load of 41,877,000 SFLs over the 20-year planning horizon. At Recycling Plant 2, the total demand for capacity was 2 units which could serve to recycle an amount of 2,538,000 SFLs in the planning horizon. It was apparent that the demanded capacity at Recycling Plant 1 was higher than that at Recycling Plant 2. However, when these expanded capacities were compared to the amount of SFLs to recycle, the capacity of both R.P. 1 and R.P. 2 were found to be consistent with the amount of SFLs to recycle in each location per year.

The optimum amount of SFLs to dispose of at different alternative sites from each generation node per year incorporating the optimum rate of recycling per year

After the input data required were entered into this decision making model, the Frontline Solver software which was run on an Excel spreadsheet was used for the computations. The optimum amount of SFLs to dispose of and the optimum percentage of recycling were different by both location and year, as was shown in Table 6.4.

Then, the total amount of environmental impact which occurred throughout the life cycle of the FL from the decisions made were calculated in a single score unit by the summation of the total amount environmental impact generated each year. This value of environmental impact which was the objective function that this model tried to minimize was 1,549,315,401 units (measured in single score unit). While the net present value (NPV) of total costs and NPV of total benefits were calculated by the summation of each year NPV. By reversed calculation, the results of this study showed that the total NPV of benefits in monetary terms was 109,152,474 baht which was more than the NPV of the total costs (100,669,963 baht). That which was associated with this decision pattern was 8,482,510 baht, approximately.

From Table 6.4, the initial rate of recycling for the first year of planning was 89%. The rate of recycling tended to decrease each year until it reached 85% (SFL recycling rate) at the end of the planning year 2026. When comparing the total amount of SFLs to be recycled each year between Recycling Plant 1 and Plant 2, the total amount for Recycling Plant 1 was found to be higher than that the total amount for Plant 2. A ratio obtained by the division of the amount of SFLs to be recycled at Recycling Plant 1 by the amount at Recycling Plant 2 in the initial year of the planning horizon was about 10.65. This ratio increased each year until it reached 14.45 at the end of the planning horizon. When comparing the total amount of SFLs to be recycled at Plant 2 to the amount of SFLs to be disposed of by non-recycling means, the total amount of SFLs at Recycling Plant 2 was found to be less than that at the non-recycling plant by about 1.43 times in first year of the planning horizon. This ratio increased each year until it reached 2.63 times at the end of planning horizon.

When considering the amount of SFLs generated in Bangkok, all of SFLs generated there were sent to be recycled at R.P. 1 each year, which was similar to the situation that occurred in Samuthprakarn. While most of the SFLs generated from Nonthaburi and Pathumthani were sent to be recycled at R.P. 2, the years 2007 and 2010 were excluded when some of generated SFLs from Nonthaburi were sent to be recycled at R.P. 1, which included some 20,224 lamps per year. At the same time, there were only two generation sources where SFLs were sent through a non-recycling process instead, namely Nakhonpathom and Samutsakhon. However, this was due to the costs and benefits constraints that affected those decision variables directly. The results of that decision, including the inventory and corresponding environmental impacts incurred by the material and energy consumption, corresponding pollutant emissions, residue waste and recovery material production, were discussed further later on.

Table 6.4 The optimum percentage of recycling SFLs each year.

Year A.D	**Place of Disposal by Recycling and Non-recycling**	**The optimum amount of SFLs decided to disposal at different alternatives from each generation node per year (lamps) incorporating the optimum percentage of recycling.**							
		Name of each generation node (province)							
		Bangkok	**Nakhon pathom**	**Nontha buri**	**Pathum thani**	**Samut prakarn**	**Samut sakhon**	**Total**	**Optimum Recycling Rate**
2007	**R.P. 1**	10,869,400	0	20,224	0	2,397,050	0	13,286,674	89%
	R.P. 2	0	0	447,746	800,111	0	0	1,247,857	
	Non-recycling	0	601,205	0	0	0	1,182,240	1,783,445	
2008	**R.P. 1**	11,298,540	0	0	0	2,531,100	0	13,829,640	89%
	R.P. 2	0	0	488,194	800,443	0	0	1,288,637	
	Non-recycling	0	641,418	0	0	0	1,278,120	1,919,538	
2009	**R.P. 1**	11,727,680	0	0	0	2,665,150	0	14,392,830	88%
	R.P. 2	0	0	508,418	800,775	0	0	1,309,193	
	Non-recycling	0	681,631	0	0	0	1,374,000	2,055,631	
2010	**R.P. 1**	12,156,820	0	20,224	0	2,799,200	0	14,976,244	88%
	R.P. 2	0	0	508,418	801,108	0	0	1,309,526	
	Non-recycling	0	721,844	0	0	0	1,469,880	2,191,724	
2011	**R.P. 1**	12,585,960	0	0	0	2,933,250	0	15,519,210	88%
	R.P. 2	0	0	548,866	801,440	0	0	1,350,306	
	Non-recycling	0	762,057	0	0	0	1,565,760	2,327,817	
2012	**R.P. 1**	13,015,100	0	0	0	3,067,300	0	16,082,400	88%
	R.P. 2	0	0	569,090	801,772	0	0	1,370,862	
	Non-recycling	0	802,270	0	0	0	1,661,640	2,463,910	
2013	**R.P. 1**	13,444,240	0	0	0	3,201,350	0	16,645,590	87%
	R.P. 2	0	0	589,314	802,104	0	0	1,391,418	
	Non-recycling	0	842,483	0	0	0	1,757,520	2,600,003	
2014	**R.P. 1**	13,873,380	0	0	0	3,335,400	0	17,208,780	87%
	R.P. 2	0	0	609,538	802,436	0	0	1,411,974	
	Non-recycling	0	882,696	0	0	0	1,853,400	2,736,096	
2015	**R.P. 1**	14,302,520	0	0	0	3,469,450	0	17,771,970	87%
	R.P. 2	0	0	629,762	802,769	0	0	1,432,531	
	Non-recycling	0	922,909	0	0	0	1,949,280	2,872,189	
2016	**R.P. 1**	14,731,660	0	0	0	3,603,500	0	18,335,160	87%
	R.P. 2	0	0	649,986	803,101	0	0	1,453,087	
	Non-recycling	0	963,122	0	0	0	2,045,160	3,008,282	
2017	**R.P. 1**	15,160,800	0	0	0	3,737,550	0	18,898,350	87%
	R.P. 2	0	0	670,210	803,433	0	0	1,473,643	
	Non-recycling	0	1,003,335	0	0	0	2,141,040	3,144,375	
2018	**R.P. 1**	15,589,940	0	0	0	3,871,600	0	19,461,540	86%
	R.P. 2	0	0	690,434	803,765	0	0	1,494,199	
	Non-recycling	0	1,043,548	0	0	0	2,236,920	3,280,468	
2019	**R.P. 1**	16,019,080	0	0	0	4,005,650	0	20,024,730	86%
	R.P. 2	0	0	710,658	804,097	0	0	1,514,755	
	Non-recycling	0	1,083,761	0	0	0	2,332,800	3,416,561	
2020	**R.P. 1**	16,448,220	0	0	0	4,139,700	0	20,587,920	86%
	R.P. 2	0	0	730,882	804,430	0	0	1,535,312	
	Non-recycling	0	1,123,974	0	0	0	2,428,680	3,552,654	
2021	**R.P. 1**	16,877,360	0	0	0	4,273,750	0	21,151,110	86%
	R.P. 2	0	0	751,106	804,762	0	0	1,555,868	
	Non-recycling	0	1,164,187	0	0	0	2,524,560	3,688,747	
2022	**R.P. 1**	17,306,500	0	0	0	4,407,800	0	21,714,300	86%
	R.P. 2	0	0	771,330	805,094	0	0	1,576,424	
	Non-recycling	0	1,204,400	0	0	0	2,620,440	3,824,840	
2023	**R.P. 1**	17,735,640	0	0	0	4,541,850	0	22,277,490	86%
	R.P. 2	0	0	791,554	805,426	0	0	1,596,980	
	Non-recycling	0	1,244,613	0	0	0	2,716,320	3,960,933	
2024	**R.P. 1**	18,164,780	0	0	0	4,675,900	0	22,840,680	86%
	R.P. 2	0	0	811,778	805,758	0	0	1,617,536	
	Non-recycling	0	1,284,826	0	0	0	2,812,200	4,097,026	
2025	**R.P. 1**	18,593,920	0	0	0	4,809,950	0	23,403,870	86%
	R.P. 2	0	0	832,002	806,091	0	0	1,638,093	
	Non-recycling	0	1,325,039	0	0	0	2,908,080	4,233,119	
2026	**R.P. 1**	19,023,060	0	0	0	4,944,000	0	23,967,060	85%
	R.P. 2	0	0	852,226	806,423	0	0	1,658,649	
	Non-recycling	0	1,365,252	0	0	0	3,003,960	4,369,212	

R.P. 1 = Recycling Plant 1(In this study this plant is located at Samuthprakarn)

R.P. 2 = Recycling Plant 2(In this study this plant is located at Pathumtani)

Non-recycling Plant = In this study, this plant is located at Raghburee, where SFLs will be stabilized, solidified and kept in a secure landfill at this place.

The resulting inventory of the decision to recycle SFLs at the optimum solution

After the optimum value of all the decision variables were obtained, the results of the optimum resulting inventory were shown in Tables 6.5 to 6.7.

In the recycling process, as detailed in Table 6.5 , the total amount of material and energy consumed in the recycling process each year tended to increase. Likewise, the amount of pollutants and cullet generated from the process tended to increase each year. The highest amount of cullet gained from this decision was 4,407,622 kg. At the same time, the highest amount of solid waste generated from the process was 40,899 kg. The ratio of the amount of cullet generated to the amount of solid waste generated was 108.

On the contrary, the SFLs that were not sent to be recycled would then be sent through the non-recycling process. At the optimum decision solution, the amount of solid waste generated was higher than that generated from the recycling process and the maximum cullet loss from the non-recycling process was 751,504 kg. The total cement consumption, which was again a major requirement of this process, was higher than that consumed in the recycling process, as was shown in Table 6.6.

Based upon the resulting transportation inventory, which was shown in Table 6.7, the transportation of the recovery material (cullet) from recycling plants to a new product manufacturing plant was found to be the largest inventory source. It was followed by the transportation of SFLs from generation node to a recycling plant, the transportation of residue waste from a recycling plant to the ultimate disposal process and lastly the transportation of SFLs from a recycling plant to a non-recycling plant, respectively.

The environmental impacts incurred due to the decision to recycle SFLs at the optimum point.

In this section of the results, the amount of total environmental impacts in single score unit was calculated. This involved combining each kind of environmental impact using the weight factors to indicate the main sources of environmental impacts that occurred each year of the planning horizon, as was shown in Table 6.8 to Table 6.10.

Table 6.5 The optimum inventory which occurred in the recycling process

Processes (Activities)	Kind of Consumption /Emission	Unit	Year																			
			2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Recycling process	Consumption																					
- At disassembly plant	Water use	m^3	2,616	2,721	2,826	2,931	3,037	3,142	3,247	3,352	3,457	3,562	3,667	3,772	3,877	3,982	4,087	4,192	4,297	4,402	4,508	4,613
	Natural gas use	m^3	669	695	722	749	776	803	830	857	883	910	937	964	991	1,018	1,045	1,071	1,098	1,125	1,152	1,179
	Electricity use	KWh	42,150	43,843	45,536	47,229	48,922	50,614	52,307	54,000	55,693	57,386	59,079	60,772	62,465	64,157	65,850	67,543	69,236	70,929	72,622	74,315
	Emission																					
	Mercury vapor emission	Kg	0.6366	0.6622	0.6877	0.7133	0.7389	0.7645	0.7900	0.8156	0.8412	0.8667	0.8923	0.9179	0.9434	0.9690	0.9946	1.0201	1.0457	1.0713	1.0968	1.1224
	Mercury in water emission	Kg	0.0107	0.0111	0.0116	0.0120	0.0124	0.0128	0.0133	0.0137	0.0141	0.0146	0.0150	0.0154	0.0159	0.0163	0.0167	0.0171	0.0176	0.0180	0.0184	0.0189
	Residual solid waste	Kg	406,967	423,312	439,657	456,002	472,346	488,691	505,036	521,381	537,726	554,071	570,416	586,761	603,106	619,450	635,795	652,140	668,485	684,830	701,175	717,520
	Cullet	Kg	2,499,939	2,600,344	2,700,748	2,801,152	2,901,557	3,001,961	3,102,365	3,202,770	3,303,174	3,403,578	3,503,983	3,604,387	3,704,791	3,805,196	3,905,600	4,006,005	4,106,409	4,206,813	4,307,218	4,407,622
- At stabilization and solidification plant	Consumption																					
	Cement use	Kg	11,395	11,853	12,310	12,768	13,226	13,683	14,141	14,599	15,056	15,514	15,972	16,429	16,887	17,345	17,802	18,260	18,718	19,175	19,633	20,091
	Sodium sulfide use	Kg	773	804	835	866	897	929	960	991	1,022	1,053	1,084	1,115	1,146	1,177	1,208	1,239	1,270	1,301	1,332	1,363
	Water use	m^3	11	12	12	13	13	14	14	15	15	16	16	16	17	17	18	18	19	19	20	20
	Electricity use	KWh	289	301	312	324	335	347	359	370	382	393	405	417	428	440	451	463	475	486	498	509
	Emission																					
	Generated solid waste	Kg	23,197	24,129	25,060	25,992	26,924	27,855	28,787	29,719	30,650	31,582	32,514	33,445	34,377	35,309	36,240	37,172	38,104	39,035	39,967	40,899

Table 6.6 The optimum inventory which occurred in the non-recycling process.

Processes (Activities)	Kind of Consumption /Emission	Unit	Year																			
			2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Non-recycling process	Consumption																					
	Cement use	Kg	356,689	383,908	411,126	438,345	465,563	492,782	520,001	547,219	574,438	601,656	628,875	656,094	683,312	710,531	737,749	764,968	792,187	819,405	846,624	873,842
	Sodium sulfide use	Kg	24,968	26,874	28,779	30,684	32,589	34,495	36,400	38,305	40,211	42,116	44,021	45,927	47,832	49,737	51,642	53,548	55,453	57,358	59,264	61,169
	Water use	m^3	357	384	411	438	466	493	520	547	574	602	629	656	683	711	738	765	792	819	847	874
	Electricity use	KWh	9,096	9,790	10,484	11,178	11,872	12,566	13,260	13,954	14,648	15,342	16,036	16,730	17,424	18,119	18,813	19,507	20,201	20,895	21,589	22,283
	Emission																					
	Mercury vapor emission	Kg	0.0795	0.0856	0.0917	0.0978	0.1038	0.1099	0.1160	0.1220	0.1281	0.1342	0.1402	0.1463	0.1524	0.1584	0.1645	0.1706	0.1767	0.1827	0.1888	0.1949
	Generated solid waste	Kg	738,346	794,689	851,031	907,374	963,716	1,020,059	1,076,401	1,132,744	1,189,086	1,245,429	1,301,771	1,358,114	1,414,456	1,470,799	1,527,141	1,583,484	1,639,826	1,696,169	1,752,511	1,808,854
	Need to extract new glass instead of cullet loss	Kg	306,753	330,161	353,569	376,977	400,385	423,793	447,201	470,609	494,017	517,425	540,833	564,240	587,648	611,056	634,464	657,872	681,280	704,688	728,096	751,504

Table 6.7 The optimum inventory which occurred from the transportation of SFLs in the SFL disposal network

Transportation		The amount of weight of transported material, W, multiplied with distance, D, (WD) prepared for calculation environmental impact happened from transportation process (kg-km)																			
From	To	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Generation Node, M	Recycling plant, I	162,250,676	169,211,057	176,376,671	183,747,518	190,707,899	197,873,513	205,039,128	212,204,742	219,370,356	226,535,970	233,701,584	240,867,198	248,032,812	255,198,427	262,364,041	269,529,655	276,695,269	283,860,883	291,026,497	298,192,111
Generation Node, M	Non-Recycling plant, NR	46,794,613	50,430,085	54,065,557	57,701,028	61,336,500	64,971,972	68,607,444	72,242,916	75,878,388	79,513,860	83,149,332	86,784,804	90,420,276	94,055,748	97,691,219	101,326,691	104,962,163	108,597,635	112,233,107	115,868,579
Recycling plant, I	New product manufacturing plant, C.	231,094,337	240,284,428	249,276,800	258,071,452	267,261,544	276,253,916	285,246,288	294,238,659	303,231,031	312,223,403	321,215,775	330,208,147	339,200,519	348,192,890	357,185,262	366,177,634	375,170,006	384,162,378	393,154,750	402,147,122
Recycling plant, I	Ultimate disposal process, S	91,901,872	95,585,832	99,254,479	102,907,814	106,591,773	110,260,421	113,929,068	117,597,715	121,266,362	124,935,010	128,603,657	132,272,304	135,940,951	139,609,598	143,278,246	146,946,893	150,615,540	154,284,187	157,952,835	161,621,482

Table 6.8 The total amount of environmental impacts (in single score unit) which occurred in each of the activities of the recycling process associated with the optimal solution

Processes (Activities)	Kind of Consumption /Emission	The amount of environmental impact (in single score unit)																			
		Year																			
		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Recycling process	Total Environmental Impact happened by consumption	4323.52	4497.16	4670.81	4844.45	5018.10	5191.74	5365.38	5539.03	5712.67	5886.32	6059.96	6233.61	6407.25	6580.89	6754.54	6928.18	7101.83	7275.47	7449.11	7622.76
- At disassembly plant	Water use	0.0054	0.0057	0.0059	0.0061	0.0063	0.0065	0.0068	0.0070	0.0072	0.0074	0.0076	0.0078	0.0081	0.0083	0.0085	0.0087	0.0089	0.0092	0.0094	0.0096
	Natural gas use	0.73	0.76	0.79	0.82	0.85	0.88	0.90	0.93	0.96	0.99	1.02	1.05	1.08	1.11	1.14	1.17	1.20	1.23	1.26	1.29
	Electricity use	4,323	4,496	4,670	4,844	5,017	5,191	5,364	5,538	5,712	5,885	6,059	6,233	6,406	6,580	6,753	6,927	7,101	7,274	7,448	7,621
	Total Environmental Impact happened by emission	8.99	9.35	9.71	10.08	10.44	10.80	11.16	11.52	11.88	12.24	12.60	12.96	13.33	13.69	14.05	14.41	14.77	15.13	15.49	15.85
	Mercury vapor emission	8.98	9.34	9.70	10.06	10.42	10.78	11.14	11.51	11.87	12.23	12.59	12.95	13.31	13.67	14.03	14.39	14.75	15.11	15.47	15.83
	Mercury in water emission	0.0115	0.0119	0.0124	0.0128	0.0133	0.0138	0.0142	0.0147	0.0151	0.0156	0.0161	0.0165	0.0170	0.0174	0.0179	0.0184	0.0188	0.0193	0.0197	0.0202
- At stabilization and solidification plant	Total Environmental Impact happened by consumption	270.60	281.47	292.34	303.21	314.07	324.94	335.81	346.68	357.55	368.41	379.28	390.15	401.02	411.89	422.75	433.62	444.49	455.36	466.23	477.09
	Cement use	238	247	257	266	276	285	295	304	314	324	333	343	352	362	371	381	390	400	409	419
	Sodium sulfide use	31	32	34	35	36	37	39	40	41	42	44	45	46	47	49	50	51	52	54	55
	Electricity use	1.77	1.84	1.91	1.98	2.05	2.12	2.20	2.27	2.34	2.41	2.48	2.55	2.62	2.69	2.76	2.83	2.91	2.98	3.05	3.12
	Total Environmental Impact happened by emission	1.82	1.89	1.96	2.04	2.11	2.18	2.26	2.33	2.40	2.48	2.55	2.62	2.70	2.77	2.84	2.91	2.99	3.06	3.13	3.21
	Generated solid waste	1.82	1.89	1.96	2.04	2.11	2.18	2.26	2.33	2.40	2.48	2.55	2.62	2.70	2.77	2.84	2.91	2.99	3.06	3.13	3.21

From Table 6.8, it was suggested that the main source of environmental impact was electricity production while the minimum environmental impact arose from mercury in the water emission.

However, from Table 6.8, it was noted, for example, in the year 2007 when all total amounts of environmental impacts occurred due to the consumption and emission from inventory analysis process, the net total amount of environmental impact was 4,604.41. At the same time, from Table 6.9, it was noted, for example, in the same year 2007, by the same calculation incorporating the amount of environmental impacts from the extraction of sand, instead of cullet loss in a non-recycling process, the net total amount environmental impact was 24,702.01.

Therefore, when comparing the net total amount of environmental impacts that resulted from the recycling to the non-recycling process, the net total amount of environmental impacts resulting from the non-recycling process were five times higher than those resulting from the recycling process at the optimal solution.

Table 6.9 The total amount of environmental impacts (in single score unit) which resulted from each activity of the non-recycling process at the optimal solution

Processes (Activities)	Kind of Comsumption /Emission	The amount of environmental impact (in single score unit)																			
		Year																			
		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Non-recycling process	Total Environmental Impact happened by consumption	8,501	9,150	9,799	10,448	11,096	11,745	12,394	13,043	13,691	14,340	14,989	15,638	16,286	16,935	17,584	18,233	18,881	19,530	20,179	20,828
	Cement use	7,440	8,007	8,575	9,143	9,710	10,278	10,846	11,414	11,981	12,549	13,117	13,684	14,252	14,820	15,388	15,955	16,523	17,091	17,658	18,226
	Sodium sulfide use	1,006	1,083	1,160	1,237	1,313	1,390	1,467	1,544	1,620	1,697	1,774	1,851	1,928	2,004	2,081	2,158	2,235	2,311	2,388	2,465
	Water use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electricity use	56	60	64	68	73	77	81	85	90	94	98	102	107	111	115	119	124	128	132	136
	Total Environmental Impact happened by emission	59.01	63.51	68.02	72.52	77.02	81.53	86.03	90.53	95.04	99.54	104.04	108.55	113.05	117.55	122.06	126.56	131.06	135.56	140.07	144.57
	Mercury vapor	1.12	1.21	1.29	1.38	1.46	1.55	1.64	1.72	1.81	1.89	1.98	2.06	2.15	2.24	2.32	2.41	2.49	2.58	2.66	2.75
	Generated solid waste	57.9	62.3	66.7	71.1	75.6	80.0	84.4	88.8	93.2	97.6	102.1	106.5	110.9	115.3	119.7	124.2	128.6	133.0	137.4	141.8
	Environmental Impact happened by extraction of sand instead of cullet loss.	11,912	12,821	13,730	14,639	15,548	16,457	17,366	18,275	19,184	20,093	21,002	21,911	22,820	23,729	24,638	25,547	26,456	27,365	28,274	29,183

Table 6.10 The total amount of environmental impacts (in single score unit) which occurred in the transportation process as a result of the decision to recycle SFLs at the optimum solution

Transportation		The total amount of environmental impact (in single score unit)																			
		Year																			
From	To	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Generation Node, M	Recycling plant, I	16,639,914	17,353,748	18,088,631	18,844,561	19,558,396	20,293,278	21,028,161	21,763,044	22,497,926	23,232,809	23,967,691	24,702,574	25,437,457	26,172,339	26,907,222	27,642,105	28,376,987	29,111,870	29,846,752	30,581,635
Generation Node, M	Non-Recycling plant, NR	4,799,107	5,171,949	5,544,792	5,917,634	6,290,476	6,663,319	7,036,161	7,409,004	7,781,846	8,154,689	8,527,531	8,900,374	9,273,216	9,646,058	10,018,901	10,391,743	10,764,586	11,137,428	11,510,271	11,883,113
Recycling plant, I	New product manufacturing plant, C.	23,700,300	24,642,807	25,565,036	26,466,988	27,409,494	28,331,723	29,253,952	30,176,181	31,098,411	32,020,640	32,942,869	33,865,098	34,787,327	35,709,556	36,631,785	37,554,014	38,476,243	39,398,472	40,320,701	41,242,930
Recycling plant, I	Ultimated disposal process, S	9,425,164	9,802,979	10,179,224	10,553,898	10,931,713	11,307,958	11,684,203	12,060,448	12,436,693	12,812,937	13,189,182	13,565,427	13,941,672	14,317,917	14,694,161	15,070,406	15,446,651	15,822,896	16,199,141	16,575,385

From the above results of the transportation inventory, it was observed that the main environmental impacts arose from the transportation of cullet from a recycling plant to a new product manufacturing plant, as were shown in Table 6.10. Because of the linearity of environmental impact functions in the distance and the transported material loads, a transportation system improvement with shorter distances may help to reduce this significant environmental impact in the SFL recycling chain.

The costs which arose from the recycling of SFLs at the optimum solution

In Table 6.11, the optimum SFL recycling costs, which integrated the optimal costs incurred from recycling and non-recycling processes, for transportation were shown by year.

Table 6.11 The costs generated from the decision to recycle SFLs at the optimum point.

Cost Category		Cost (Baht)																				
		Year																				
		2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Total
Recycling process Cost	Cost of all consumed raw material &energy																					
	-Water	28,648	29,798	30,949	32,099	33,250	34,400	35,551	36,702	37,852	39,003	40,153	41,304	42,454	43,605	44,755	45,906	47,057	48,207	49,358	50,508	791,558
	-Natural gas	6,017	6,259	6,501	6,742	6,984	7,226	7,467	7,709	7,951	8,192	8,434	8,676	8,917	9,159	9,401	9,642	9,884	10,126	10,367	10,609	166,263
	-Electricity	117,097	121,800	126,503	131,206	135,909	140,612	145,315	150,018	154,721	159,424	164,127	168,830	173,533	178,236	182,939	187,641	192,344	197,047	201,750	206,453	3,235,506
	Cost of disposal residue waste	2,848,768	2,963,182	3,077,597	3,192,011	3,306,425	3,420,839	3,535,254	3,649,668	3,764,082	3,878,496	3,992,911	4,107,325	4,221,739	4,336,153	4,450,568	4,564,982	4,679,396	4,793,810	4,908,225	5,022,639	78,714,070
	Labor cost	17,091,532	17,777,974	18,464,416	19,150,859	19,837,301	20,523,743	21,210,186	21,896,628	22,583,070	23,269,512	23,955,955	24,642,397	25,328,839	26,015,282	26,701,724	27,388,166	28,074,608	28,761,051	29,447,493	30,133,935	472,254,672
	Land Rent & Maintenace Cost	14,400,000	2,400,000	0	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	1,200,000	42,000,000
	Investment cost	33,120,000	5,520,000	0	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	2,760,000	96,600,000
	-Machine	22,320,000	3,720,000	0	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	1,860,000	65,100,000
	-Construction facilities	10,800,000	1,800,000	0	900,000	900,000	1,800,000	900,000	900,000	900,000	1,800,000	900,000	900,000	900,000	1,800,000	900,000	900,000	1,800,000	900,000	900,000	900,000	31,500,000
	Total recycling cost	67,612,062	28,819,014	21,705,966	26,472,917	27,279,869	32,046,821	28,893,772	29,700,724	30,507,676	35,274,628	32,121,579	32,928,531	33,735,483	38,502,434	35,349,386	36,156,338	40,923,290	37,770,241	38,577,193	39,384,145	693,762,069
Total non-recycling cost		2,496,823	2,687,353	2,877,883	3,068,414	3,258,944	3,449,474	3,640,004	3,830,534	4,021,065	4,211,595	4,402,125	4,592,655	4,783,185	4,973,716	5,164,246	5,354,776	5,545,306	5,735,836	5,926,367	6,116,897	86,137,198
The total transportation Cost		1,276,316	1,340,182	1,405,225	1,471,443	1,535,310	1,600,352	1,665,395	1,730,437	1,795,480	1,860,522	1,925,565	1,990,607	2,055,649	2,120,692	2,185,734	2,250,777	2,315,819	2,380,862	2,445,904	2,510,947	37,863,218
Total Cost		71,385,201	32,846,549	25,989,074	31,012,774	32,074,123	37,096,647	34,199,171	35,261,696	36,324,220	41,346,744	38,449,269	39,511,793	40,574,318	45,596,842	42,699,366	43,761,891	48,784,415	45,886,939	46,949,464	48,011,988	817,762,485
Net Present Value (NPV)		71,385,201	15,940,854	6,121,170	3,544,917	1,779,271	998,720	446,834	223,592	111,782	61,750	27,868	13,898	6,926	3,778	1,717	854	462	211	105	52	**100,669,963**

The benefits gained from recycling SFLs at the optimum solution

As mentioned in the previous chapter, the benefits gained from this decision were divided into two parts which included revenue from SFL disposal costs and revenue from the selling of recovery materials (cullet), as was shown in Table 6.12. In this table the total benefits and NPV were indicated.

Table 6.12 The benefits generated from the decision to recycle SFLs at the optimum Solution.

Benefit Category	Benefit (Baht)																				
	Year																				
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Total
Revenue from SFL disposal cost	48,953,928	51,113,446	53,272,963	55,432,481	57,591,998	59,751,516	61,911,034	64,070,551	66,230,069	68,389,586	70,549,104	72,708,622	74,868,139	77,027,657	79,187,174	81,346,692	83,506,210	85,665,727	87,825,245	89,984,762	1,389,386,904
Revenue from selling recovery material (cullet)	4,999,879	5,200,687	5,401,496	5,602,305	5,803,113	6,003,922	6,204,731	6,405,540	6,606,348	6,807,157	7,007,966	7,208,774	7,409,583	7,610,392	7,811,200	8,012,009	8,212,818	8,413,626	8,614,435	8,815,244	138,151,225
Total Benefit	53,953,807	56,314,133	58,674,459	61,034,786	63,395,112	65,755,438	68,115,764	70,476,091	72,836,417	75,196,743	77,557,070	79,917,396	82,277,722	84,638,048	86,998,375	89,358,701	91,719,027	94,079,354	96,439,680	98,800,006	1,527,538,129
NPV of Total Benefit	53,953,807	27,329,975	13,819,514	6,976,586	3,516,763	1,770,275	889,977	446,884	224,142	112,304	56,213	28,111	14,046	7,012	3,498	1,744	869	432	215	107	109,152,474

6.3 The sensitivity analysis

Sensitivity analyses were performed to investigate how the optimum solutions of the above base model would respond to changes in key parameters. The analyses herein suggested that if there was necessarily substantial uncertainty in assumed growth rates of SFL loads, interest and inflation rates would be employed. The sensitivity of the optimal capacity expansion path to such changes was evaluated over the feasible solution space of the base model.

One of the significant indicators in the sensitivity analysis was the elasticity which represents the percent of change in value of the output model data per a percent of relative change in the input parameter of the model. The calculated elasticity was determined by the following equations:

Relative change in the parameter value

$$= \frac{\underline{\text{Different value changed of parameter}}}{\text{Base model parameter value}} \times 100\% \qquad (6.5)$$

$$\text{Elasticity} = \frac{\underline{\text{Percent changed in value of output model data}}}{\text{Relative change in the parameter value}} \times 100\% \qquad (6.6)$$

6.3.1 A sensitivity analysis on the rate of SFL load growth (ROG)

SFL load growth sensitivity analyses were performed by varying the rates of growth (ROG) of the SFLs. The relative change in ROG were varied from -40 %, 15%, 50% to 100%, respectively. The results representing the elasticity of the changes in the recycling rate to the changes in ROG parameters were shown in Tables 6.13 to 6.16. By varying the recycling rate over various relative changes in ROG, results indicated that the rate of recycling did not change if the relative change in ROG was higher than -40%. When the relative change in the ROG was higher than 15%, the recycling rate did change. Tables 6.13 to 6.16 indicate using the same relative change in ROG, the change in the recycling rates in the final year of the planning horizon was higher than that of the initial year in light of the elasticity. Furthermore, when the values of elasticity shown in Figure 6.14 were compared, the elasticity corresponding to 100% of relative change in ROG was the lowest positive value. In conclusion, these results have shown that the rate of recycling each year is highly sensitive at a lower percent of change in ROG.

The results of the sensitivity analysis of the recycling plant capacity at various relative changes in ROG were shown in Table 6.17. From this table, the total requirement of expanded capacity of the recycling plant was sensitive only at 50% and 100% of relative change in ROG. The elasticity was 0.06 at 50% of relative change in ROG and doubled to 0.12 at 100% of relative change in ROG.

The environmental impacts (the objective function) were changed over the various relative changes in ROG in which all elasticity changes were equal as shown in the results of Table 6.18; while the elasticity of net benefits (model constraint) over various relative changes in ROG were shown in Table 6.19

Table 6.13 The sensitivity analysis of the rate of SFL load growth when the change in ROG was -0.4B (Relative change in ROG = -40 %), B = ROG of base case

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	ROG Changed to = 0.6B			
1	89.07	89.07	0.00	0.00	0.000
2	88.73	88.86	0.13	0.15	-0.004
3	88.42	88.67	0.25	0.28	-0.007
4	88.14	88.48	0.35	0.39	-0.010
5	87.87	88.31	0.43	0.49	-0.012
6	87.63	88.14	0.51	0.58	-0.015
7	87.40	87.98	0.58	0.66	-0.016
8	87.19	87.82	0.64	0.73	-0.018
9	86.99	87.68	0.69	0.79	-0.020
10	86.80	87.54	0.73	0.84	-0.021
11	86.63	87.40	0.77	0.89	-0.022
12	86.46	87.27	0.81	0.93	-0.023
13	86.31	87.15	0.84	0.97	-0.024
14	86.16	87.03	0.87	1.00	-0.025
15	86.03	86.91	0.89	1.03	-0.026
16	85.89	86.80	0.91	1.06	-0.026
17	85.77	86.70	0.93	1.08	-0.027
18	85.65	86.60	0.94	1.10	-0.028
19	85.54	86.50	0.96	1.12	-0.028
20	85.43	86.40	0.97	1.13	-0.028

Table 6.14 The sensitivity analysis of the rate of SFL load growth when the change in ROG was 0.15B (Relative change in ROG = 15%), B = ROG of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rate	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	ROG Changed to = 1.15B			
1	89.07	89.07	0.00	0.00	0.000
2	88.73	88.69	-0.05	-0.05	-0.004
3	88.42	88.34	-0.09	-0.10	-0.007
4	88.14	88.02	-0.12	-0.14	-0.009
5	87.87	87.73	-0.15	-0.17	-0.011
6	87.63	87.46	-0.17	-0.20	-0.013
7	87.40	87.21	-0.19	-0.22	-0.015
8	87.19	86.98	-0.21	-0.24	-0.016
9	86.99	86.77	-0.22	-0.26	-0.017
10	86.80	86.57	-0.23	-0.27	-0.018
11	86.63	86.39	-0.24	-0.28	-0.019
12	86.46	86.21	-0.25	-0.29	-0.019
13	86.31	86.05	-0.26	-0.30	-0.020
14	86.16	85.90	-0.26	-0.30	-0.020
15	86.03	85.76	-0.27	-0.31	-0.021
16	85.89	85.62	-0.27	-0.31	-0.021
17	85.77	85.50	-0.27	-0.32	-0.021
18	85.65	85.38	-0.28	-0.32	-0.021
19	85.54	85.26	-0.28	-0.32	-0.022
20	85.43	85.16	-0.28	-0.33	-0.022

Table 6.15 The sensitivity analysis of the rate of SFL load growth when the change in ROG was 0.5B (Relative change in ROG = 50%), B = ROG of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	ROG Changed to = 1.5B			
1	89.07	89.07	0.00	0.00	0.000
2	88.73	88.58	-0.16	-0.18	-0.004
3	88.42	88.14	-0.29	-0.32	-0.006
4	88.14	87.75	-0.39	-0.44	-0.009
5	87.87	87.40	-0.47	-0.54	-0.011
6	87.63	87.09	-0.54	-0.62	-0.012
7	87.40	86.80	-0.60	-0.68	-0.014
8	87.19	86.55	-0.64	-0.74	-0.015
9	86.99	86.31	-0.68	-0.78	-0.016
10	86.80	86.09	-0.71	-0.82	-0.016
11	86.63	85.89	-0.73	-0.85	-0.017
12	86.46	85.71	-0.75	-0.87	-0.017
13	86.31	85.54	-0.77	-0.89	-0.018
14	86.16	85.38	-0.78	-0.91	-0.018
15	86.03	85.23	-0.79	-0.92	-0.018
16	85.89	85.10	-0.80	-0.93	-0.019
17	85.77	84.97	-0.80	-0.93	-0.019
18	85.65	84.85	-0.80	-0.94	-0.019
19	85.54	84.73	-0.81	-0.94	-0.019
20	85.43	84.63	-0.81	-0.94	-0.019

Table 6.16 The sensitivity analysis of the rate of SFL load growth when the change in ROG was 1B (Relative change in ROG = 100%), B = ROG of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	ROG Changed to = 2B			
1	89.07	89.07	0.00	0.00	0.000
2	88.73	88.42	-0.31	-0.35	-0.003
3	88.42	87.87	-0.55	-0.62	-0.006
4	88.14	87.40	-0.74	-0.84	-0.008
5	87.87	86.99	-0.88	-1.01	-0.010
6	87.63	86.63	-1.00	-1.14	-0.011
7	87.40	86.31	-1.09	-1.25	-0.012
8	87.19	86.03	-1.16	-1.33	-0.013
9	86.99	85.77	-1.22	-1.40	-0.014
10	86.80	85.54	-1.26	-1.46	-0.015
11	86.63	85.33	-1.30	-1.50	-0.015
12	86.46	85.14	-1.32	-1.53	-0.015
13	86.31	84.97	-1.34	-1.55	-0.016
14	86.16	84.81	-1.35	-1.57	-0.016
15	86.03	84.66	-1.36	-1.58	-0.016
16	85.89	84.53	-1.37	-1.59	-0.016
17	85.77	84.40	-1.37	-1.60	-0.016
18	85.65	84.28	-1.37	-1.60	-0.016
19	85.54	84.18	-1.36	-1.59	-0.016
20	85.43	84.07	-1.36	-1.59	-0.016

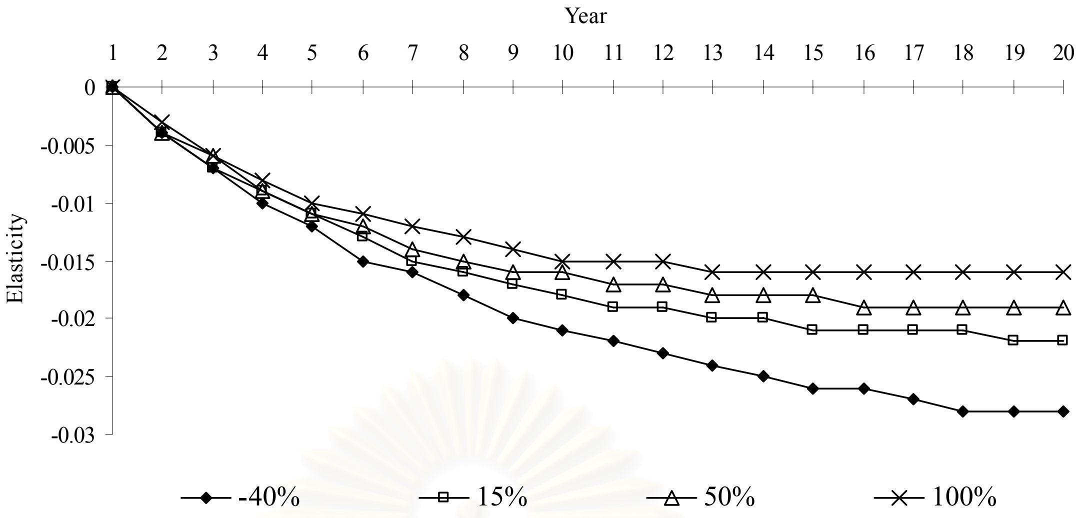


Figure 6.14 The elasticity of changes in the SFL recycling rate at various relative changes in ROG each year.

Table 6.17 The sensitivity of the recycling plant capacity at various relative changes in ROG.

Year	Optimum Capacity (Unit)					Different Optimum Capacities				Different Percentages of Optimum Capacity				Elasticity			
	Base Case	-40 %	15 %	50 %	100 %	-40 %	15 %	50 %	100 %	-40 %	15 %	50 %	100 %	-40 %	15 %	50%	100 %
1	11	11	11	11	11	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	2	0	0	0	1	0	0	0	100	0	0	0	1
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1	1	1	1	2	0	0	0	1	0	0	0	100	0	0	0	1
5	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	2	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
7	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
8	1	1	1	1	2	0	0	0	1	0	0	0	100	0	0	0	1
9	1	1	2	2	1	0	1	1	0	0	100	100	0	0	6.67	2	0
10	2	2	1	1	2	0	-1	-1	0	0	-50	-50	0	0	-3.33	-1	0
11	1	1	1	2	2	0	0	1	1	0	0	100	100	0	0	2	1
12	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
13	1	1	2	1	1	0	1	0	0	0	100	0	0	0	6.67	0	0
14	2	2	1	1	1	0	-1	-1	-1	0	-50	-50	-50	0	-3.33	-1	-0.5
15	1	1	1	2	2	0	0	1	1	0	0	100	100	0	0	2	1
16	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
17	2	2	2	1	2	0	0	-1	0	0	0	-50	0	0	0	-1	0
18	1	1	1	2	1	0	0	1	0	0	0	100	0	0	0	2	0
19	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
20	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Total	**33**	**33**	**33**	**34**	**37**	**0**	**0**	**1**	**4**	**0**	**0**	**3**	**12**	**0**	**0**	**0.06**	**0.12**

Table 6.18 The environmental impacts changed at various relative changes in ROG.

Relative change in ROG	Total Environmental impact of base case	Total Environmental impact at various relative change in ROG	Difference of Total environmental impact	Percent difference of total environmental impact	Elasticity
-40%	1,549,315,401	1,366,299,667	-183,015,733	-11.81	0.295
15%	1,549,315,401	1,617,941,625	68,626,224	4.43	0.295
50%	1,549,315,401	1,778,069,478	228,754,077	14.76	0.295
100%	1,549,315,401	2,006,823,561	457,508,161	29.53	0.295

Table 6.19 The sensitivity of net benefit at various relative changes in ROG.

Relative change in ROG	Difference in values between benefit and cost (net benefit)of base case	Difference in value between benefit and cost (net benefit) at various relative changes in ROG	Difference of net benefit	Percent difference of net benefit	Elasticity
-40%	8,482,510	7,521,780	-960730.21	-11.33	0.283
15%	8,482,510	8,832,333	349823.25	4.12	0.275
50%	8,482,510	9,661,701	1179190.44	13.90	0.278
100%	8,482,510	8,456,500	-26010.00	-0.31	-0.003

6.3.2 The sensitivity analysis of the interest rates (IR)

The sensitivity analyses of the optimal solution for interest rates were performed by varying the interest rate (IR). Based upon relative changes in the ROG from 2%, 25%, 50% and 100% respectively, the resulting elasticity representing the change in the recycling rate to IR were obtained and shown in Tables 6.20 to 6.22. In light of the changes of the recycling rate at various relative changes in the IR, the results of the sensitivity analysis suggested that the rate of recycling was not sensitive to 2% or less than that of the relative changes in the IR. It was noted that most of changes in the recycling rate at various relative changes in the IR occurred beginning in the initial year and lasting until the third year of the planning horizon. At the same time, the recycling rate was not affected by the changes in the IR, for example, beginning in the fourth year of the planning horizon and lasting till the end of the planning horizon, at 100% of relative change in the IR. However, as was seen in Figure (6.15), the elasticity of 50% of relative change in the IR was found to be the highest value, followed by 100% and 25%, respectively. In conclusion, these results indicated that the recycling rate was averagely sensitive to the higher percent changes in the IR each year.

Table 6.20 The sensitivity analysis of interest rates to a change of 2B in interest rate (Relative change in interest rate = 100%), B = interest rate of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	Interest Rate Changed to = 2B			
1	89.07	60.27	-28.80	-32.33	-0.323
2	88.73	85.15	-3.59	-4.04	-0.040
3	88.42	85.45	-2.97	-3.36	-0.034
4	88.14	88.14	0	0	0
5	87.87	87.87	0	0	0
6	87.63	87.63	0	0	0
7	87.40	87.40	0	0	0
8	87.19	87.19	0	0	0
9	86.99	86.99	0	0	0
10	86.80	86.80	0	0	0
11	86.63	86.63	0	0	0
12	86.46	86.46	0	0	0
13	86.31	86.31	0	0	0
14	86.16	86.16	0	0	0
15	86.03	86.03	0	0	0
16	85.89	85.89	0	0	0
17	85.77	85.77	0	0	0
18	85.65	85.65	0	0	0
19	85.54	85.54	0	0	0
20	85.43	85.43	0	0	0

Table 6.21 The sensitivity analysis of interest rates to a change of 1.5B in interest rate (Relative change in interest rate = 50%), B = interest rate of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	Interest Rate Changed to = 1.5B			
1	89.07	73.48	-15.59	-17.50	-0.350
2	88.73	88.73	0	0	0
3	88.42	88.42	0	0	0
4	88.14	88.14	0	0	0
5	87.87	87.87	0	0	0
6	87.63	87.63	0	0	0
7	87.40	87.40	0	0	0
8	87.19	87.19	0	0	0
9	86.99	86.99	0	0	0
10	86.80	86.80	0	0	0
11	86.63	86.63	0	0	0
12	86.46	86.46	0	0	0
13	86.31	86.31	0	0	0
14	86.16	86.16	0	0	0
15	86.03	86.03	0	0	0
16	85.89	85.89	0	0	0
17	85.77	85.77	0	0	0
18	85.65	85.65	0	0	0
19	85.54	85.54	0	0	0
20	85.43	85.43	0	0	0

Table 6.22 The sensitivity analysis of interest rates to a change of 1.25 in interest rate (Relative change in interest rate = 25%), B = interest rate of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rate (%)	Elasticity
	Base Case = B	Interest Rate Changed to = 1.25B			
1	89.07	88.50	-0.57	-0.64	-0.025
2	88.73	88.73	0	0	0
3	88.42	88.42	0	0	0
4	88.14	88.14	0	0	0
5	87.87	87.87	0	0	0
6	87.63	87.63	0	0	0
7	87.40	87.40	0	0	0
8	87.19	87.19	0	0	0
9	86.99	86.99	0	0	0
10	86.80	86.80	0	0	0
11	86.63	86.63	0	0	0
12	86.46	86.46	0	0	0
13	86.31	86.31	0	0	0
14	86.16	86.16	0	0	0
15	86.03	86.03	0	0	0
16	85.89	85.89	0	0	0
17	85.77	85.77	0	0	0
18	85.65	85.65	0	0	0
19	85.54	85.54	0	0	0
20	85.43	85.43	0	0	0

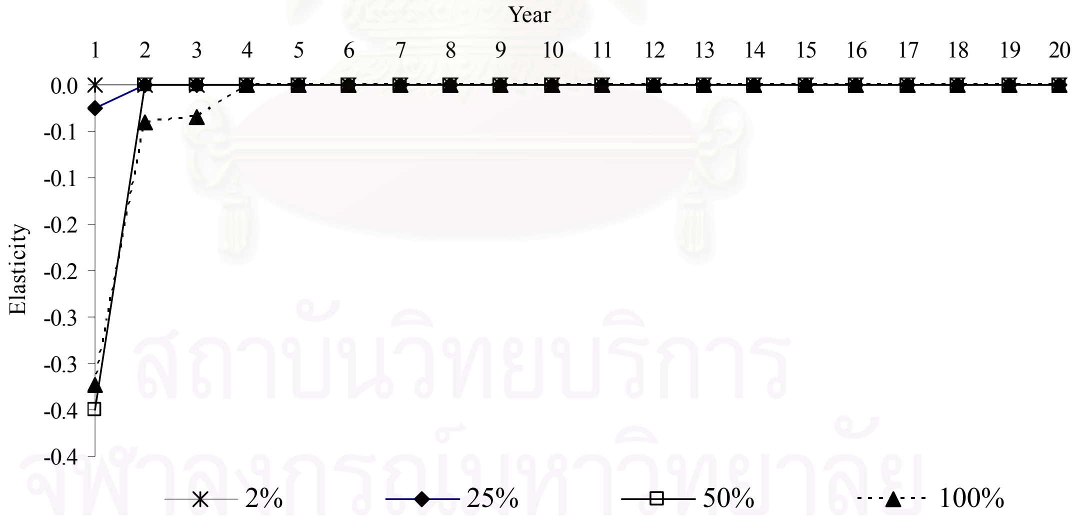


Figure 6.15 The elasticity of changes in the SFL recycling rate to various relative changes in interest rates each year.

Moreover, the results of the sensitivity analysis of the recycling plant capacity at various relative changes in the IR were shown in Table 6.23. From this table, the total demand for the additional capacity of recycling plants happened only at 25%, 50% and 100% of relative change in the IR. The highest elasticity was 1.7 at 25% of relative change in the IR.

Table 6.23 The sensitivity of recycling plant capacity to various relative changes in interest rate.

Year	Optimum Capacity (Unit)					Different Optimum Capacities				Different Percentages of Optimum Capacities				Elasticity			
	Base Case	2 %	25 %	50 %	100 %	2 %	25 %	50 %	100 %	2 %	25 %	50 %	100 %	2 %	25 %	50 %	100 %
1	11	11	11	9	7	0	0	-2	-4	0	0	-18	-36	0	0	-0.36	-0.36
2	1	1	0	2	4	0	-1	1	3	0	-100	100	300	0	-4	2	3
3	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0
4	1	1	0	0	1	0	-1	-1	0	0	-100	-100	0	0	-4	-2	0
5	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	2	1	0	2	0	-1	-2	0	-2	-50	-100	0	-100	-25	-4	0	-1
7	1	2	1	1	1	1	0	0	0	100	0	0	0	50	0	0	0
8	1	1	0	1	0	0	-1	0	-1	0	-100	0	-100	0	-4	0	-1
9	1	1	1	2	1	0	0	1	0	0	0	100	0	0	0	2	0
10	2	2	0	1	0	0	-2	-1	-2	0	-100	-50	-100	0	-4	-1	-1
11	1	1	0	1	0	0	-1	0	-1	0	-100	0	-100	0	-4	0	-1
12	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
13	1	1	0	2	0	0	-1	1	-1	0	-100	100	-100	0	-4	2	-1
14	2	2	1	1	1	0	-1	-1	-1	0	-50	-50	-50	0	-2	-1	-0.5
15	1	1	0	1	0	0	-1	0	-1	0	-100	0	-100	0	-4	0	-1
16	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
17	2	1	0	2	0	-1	-2	0	-2	-50	-100	0	-100	-25	-4	0	-1
18	1	2	0	1	0	1	-1	0	-1	100	-100	0	-100	50	-4	0	-1
19	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
20	1	1	0	1	0	0	-1	0	-1	0	-100	0	-100	0	-4	0	-1
Total	**33**	**33**	**19**	**32**	**19**	**0**	**-14**	**-1**	**-14**	**0**	**-42**	**-3**	**-42**	**0**	**-1.7**	**-0.06**	**-0.42**

In light of the environmental impact (the objective function) which changed at various relative changes in the IR, the elasticity was zero at 2% and 25% of relative change in the IR. However, the elasticity at 50% of relative change in the IR was 0.003, and it increased to 0.004 at 100% of relative change in the IR, as was shown in Table 6.24.

Table 6.24 The environmental impact changes at various relative changes in interest rate.

Relative change in interest rate	Total Environmental impact of base case	Total Environmental impact at various relative change in interest rate	Difference of Total environmental impact	Percent difference of total environmental impact	Elasticity
2%	1,549,315,401	1,549,315,401	0.00	0.00	0.000
25%	1,549,315,401	1,549,315,401	0.00	0.00	0.000
50%	1,549,315,401	1,551,640,091	2324690.07	0.15	0.003
100%	1,549,315,401	1,555,033,085	5717684.33	0.37	0.004

From Table 6.25, results showed the elasticity of 2% in the IR change was 5.070 and was reduced to 0.798 for 100% in the IR change.

Table 6.25 The sensitivity of the net benefit at various relative changes in interest rate

Relative change in interest rate	Difference in values between benefit and cost (net benefit)of base case	Difference in value between benefit and cost (net benefit) at various relative changes in interest rate	Difference of net benefit	Percent difference of net benefit	Elasticity
2%	8,482,510	7,622,389	-860120.99	-10.14	-5.070
25%	8,482,510	1,554,930	-6927580.17	-81.67	-3.267
50%	8,482,510	930,251	-7552259.28	-89.03	-1.781
100%	8,482,510	1,711,774	-6770736.06	-79.82	-0.798

6.3.3 The sensitivity analysis of the inflation rate (IFR)

The sensitivity analyses of inflation rates were also performed by varying the inflation rate (IFR) from -50% and -100%, respectively. The results representing the elasticity of the changes in the recycling rates to the changes in the IFR parameters were shown in Tables 6.26 and 6.27. In light of the changes in the recycling rates to various relative changes in the IFR, results suggested that the rate of recycling went unchanged if the relative change in the IFR was higher than -50% approximately. Most of the changes in the recycling rates, which occurred at various relative changes in the IFR, happened starting in the first year and lasting till the third year of the planning horizon. At the same time, the recycling rates were not affected by the change in the IFR, for example, from the fourth year till the end of the planning horizon when the relative change in the IFR was at -50%. However, as was seen in Figure 6.16, the elasticity of -50% of relative change in the IFR had the highest value when compared to -100% of relative change in the IFR, within the first 3 years of the planning horizon. In conclusion, the results indicated that the rate of recycling in each year was positively highly sensitive to lower negative percent changes in the IFR.

Moreover, the results suggested that the recycling plant capacity was sensitive to various relative changes in the IFR, as was shown in Table 6.28. From this table, the total requirement of expanded capacity of the recycling plant was changed both at -50% and -100% of relative change in the IFR. The highest elasticity was 0.85 at -50% of relative change in the IFR and was reduced to 0.4 at -100% of relative change in the IFR.

Table 6.26 The sensitivity analysis of the inflation rate with a change of 0.5B in the inflation rate (Relative change in inflation rate = -50%), B = inflation rate of base case

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rates (%)	Elasticity
	Base Case = B	Inflation rate Changed to = 0.5 B			
1	89.07	64.90	-24.17	-27.13	0.543
2	88.73	85.39	-3.34	-3.77	0.075
3	88.42	84.78	-3.64	-4.12	0.082
4	88.14	88.14	0	0	0
5	87.87	87.88	0	0	0
6	87.63	87.63	0	0	0
7	87.40	87.40	0	0	0
8	87.19	87.19	0	0	0
9	86.99	86.99	0	0	0
10	86.80	86.81	0	0	0
11	86.63	86.63	0	0	0
12	86.46	86.47	0	0	0
13	86.31	86.31	0	0	0
14	86.16	86.17	0	0	0
15	86.03	86.03	0	0	0
16	85.89	85.90	0	0	0
17	85.77	85.77	0	0	0
18	85.65	85.66	0	0	0
19	85.54	85.54	0	0	0
20	85.43	85.44	0	0	0

Table 6.27 The sensitivity analysis of the inflation rate with a change of 0B in the inflation rate (Relative change in inflation rate = -100%), B = inflation rate of base case.

Year	Optimum Recycling Rate		Different Optimum Recycling Rates	Relative Changes in Recycling Rates (%)	Elasticity
	Base Case = B	Inflation rate changed to = 0 B			
1	89.07	50.09	-38.98	-43.77	0.438
2	88.73	88.73	0	0	0
3	88.42	88.42	0	0	0
4	88.14	88.14	0	0	0
5	87.87	87.88	0	0	0
6	87.63	87.63	0	0	0
7	87.40	87.40	0	0	0
8	87.19	87.19	0	0	0
9	86.99	86.99	0	0	0
10	86.80	86.81	0	0	0
11	86.63	86.63	0	0	0
12	86.46	86.47	0	0	0
13	86.31	86.31	0	0	0
14	86.16	86.17	0	0	0
15	86.03	86.03	0	0	0
16	85.89	85.90	0	0	0
17	85.77	85.77	0	0	0
18	85.65	85.66	0	0	0
19	85.54	85.54	0	0	0
20	85.43	85.44	0	0	0

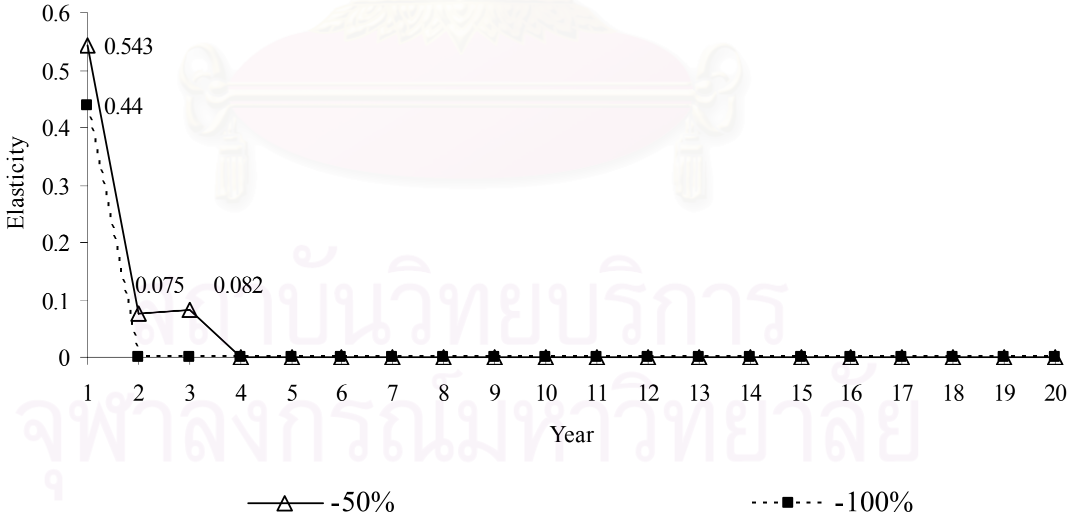


Figure 6.16 The elasticity of changes in the SFL recycling rate at various relative changes in the inflation rates each year.

Table 6.28 The sensitivity of recycling plant capacity at various relative changes in the inflation rate.

Year	Optimum Capacity (Unit)			Different Optimum Capacity		Different Percentage of Optimum Capacities		Elasticity	
	Base Case	-50%	-100%	-50%	-100%	-50%	-100%	-50%	-100%
1	11	8	6	-3	-5	-27	-45	0.55	0.45
2	1	3	5	2	4	200	400	-4	-4
3	0	0	1	0	1	0	0	0	0
4	1	1	0	0	-1	0	-100	0	1
5	1	1	1	0	0	0	0	0	0
6	2	0	0	-2	-2	-100	-100	2	1
7	1	1	1	0	0	0	0	0	0
8	1	0	0	-1	-1	-100	-100	2	1
9	1	1	1	0	0	0	0	0	0
10	2	0	0	-2	-2	-100	-100	2	1
11	1	0	0	-1	-1	-100	-100	2	1
12	1	1	1	0	0	0	0	0	0
13	1	0	0	-1	-1	-100	-100	2	1
14	2	1	1	-1	-1	-50	-50	1	0.5
15	1	0	0	-1	-1	-100	-100	2	1
16	1	1	1	0	0	0	0	0	0
17	2	0	0	-2	-2	-100	-100	2	1
18	1	0	0	-1	-1	-100	-100	2	1
19	1	1	1	0	0	0	0	0	0
20	1	0	1	-1	0	-100	0	2	0
Total	33	19	20	-14	-13	-42	-39	0.85	0.40

In view of the environmental impacts (objective function) which changed with various relative changes in the IFR, the elasticity at -50% of relative change in the IFR was -0.007, and 0.004 at -100% of relative change in the IFR, as the results were shown in Table 6.29.

Table 6.29 The environmental impact change at various relative changes in inflation rate.

Relative change in inflation rate	Total Environmental impact of base case	Total Environmental impact at various relative change in inflation rate	Difference of Total environmental impact	Percent difference of total environmental impact	Elasticity
-50%	1,549,315,401	1,554,530,872	5215471.13	0.34	-0.007
-100%	1,549,315,401	1,555,535,469	6220068.68	0.40	-0.004

The elasticity changes of the net benefit (model constraint) at various relative changes in the IFR were shown in Table 6.30. The elasticity for -50% of the IFR change was 1.685 and was reduced to 0.943 for -100% of the IFR change.

Table 6.30 The sensitivity of net benefit at various relative changes in the inflation rate.

Relative changes in the inflation rate.	Difference in value between benefit and cost (net benefit) of base case	Difference in value between the benefit and cost (net benefit) at various relative changes in the inflation rate	Difference of net benefit	Percent difference of net benefit	Elasticity
-50%	8,482,510	1,335,849	-7146661.53	-84.25	1.685
-100%	8,482,510	485,283	-7997227.27	-94.28	0.943

However, in this study, other model parameters such as the investment costs, operation and maintenance costs, recovery material price, fuel price including the normalization and weighing factors in the environmental impact assessment, were also investigated. The results showed that in the ranges from -100% to 100% of these parameters changes, the rates of recycling and the expanded capacities were not affected.

CHAPTER VII

CONCLUSION

7.1 Conclusion

The conclusion of this study was divided into two parts. The first part was the conclusion of an application of the LCA to assess the environmental impacts of SFL disposal at the various recycling rates ranging from 0-100% in Thailand. The second part was the results from the development and application of the decision making model for the optimal recycling of SFLs in the study area.

In the first part, an application of the LCA to assess the environmental impacts of SFL disposal at the various recycling rates ranging from 0-100% in Thailand was conducted. The analysis carried out in this study showed that the main contributors to the environmental impacts were cement production, sodium sulfide production, and electricity production, respectively. Of these, at all recycling rates, cement production was found to be the main contributor (more than 90%) of carcinogens, climate change, acidification/eutrophication and land use. Sodium sulfide production was the second largest contributor of respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use and minerals. Moreover, about 16% of contribution to carcinogens, respiratory organics, respiratory organics, climate change, ecotoxicity and acidification/eutrophication came from electricity production. New glass production showed a small contribution (about 1%) to the respiratory organics, respiratory inorganics and ozone layer. Mercury vapor emissions also made a small contribution to carcinogens and ecotoxicity. For solid waste landfilling, a small contribution to respiratory organics and inorganics, ozone layer, acidification/eutrophication and minerals was observed. Other activities during the life cycle of FLs were not observed for their contributions to these 10 environmental impact potentials. However, it is anticipated that impacts would be reduced when the rate of recycling is increased. Therefore, all specified environmental impacts would be reduced with the reduction of the use of cement in the disposal process. This conclusion was supported by results from the inventory analysis. They indicated that the non-recycling process (100% landfill) produced more cement than recycling, as most of the cement was consumed in the stabilization and solidification processes before entering the landfill.

However, due to the existing technology for the recycling of SFLs which was selected for this study, only the cullet could be recycled. There were residue wastes generated from the disassembly process at the recycling plant. These residue wastes needed to go through the stabilization and solidification processes before being dumped securely in a landfill. For this reason, cement and sodium sulfide were two major substances required for these processes in large amounts. At the same time, the production of these materials generated a high environmental impact. Hence, this explanation indicates the reasons why cement production showed up as a major source of environmental impact.

Therefore, a distinct selection of technology used for the recycling of other kinds of recovery materials may help to reduce the amount of sodium sulfide and cement production in the stabilization and solidification processes, respectively. This will help to reduce the environmental impact of these productions in the future.

In the second part, a model was applied for a case study area in Bangkok and the vicinity. The main results for the optimum recycling rate, expansion capacity, and time for recycling plant capacity expansion were calculated. Two potential SFL recycling plants were selected in the study area for the purpose of this study. The first one was located in Samutprakarn province, Recycling Plant 1 (R.P.1). The second was sited in Pathumthani province, Recycling Plant 2 (R.P.2). The criteria for these selections was explained in chapter V. The initial requirements of the recycling capacity obtained from the model results showed recycling plant 1 in the first year should be started at eleven units with a upper bound capacity of 13,959,000 lamps per year. The required capacity expansion of R.P.1 tended to show an increase every year within a 20 year planning horizon, excluded only in the third year. While the initial requirement for the capacity of recycling plant 2 showed that it should be started at one unit for the first year, it increased to two units in the second year. The total requirement of the recycling plant capacity at R.P.1 was 33 units of recycling which could serve to recycle 41,877,000 SFLs within a 20-year planning horizon. While, at R.P.2, the total requirement for the recycling plant capacity was 2 units of recycling which could serve to recycle 2,538,000 SFLs within the planning time.

In order for the optimum recycling rate to be found for each year of the planning horizon, the initial rate of recycling in the first year of planning was 89%. The rate of recycling tended to fall each year until it reached 85% (SFL recycling rate) at the end of that planning year (year 2026). When comparing the total amount of SFLs to be recycled between R.P.1 and R.P.2 each year, the total amount of SFLs at R.P.1 was higher than the total amount of SFLs to be recycled at R.P.2.

However, in this study, the amount of SFLs inputted into the model for application were all SFLs assumed to be generated from each source in the case study area. Furthermore, all SFLs generated had to be collected and sent for disposal either by recycling or non-recycling, with absolutely no lamps leaking in a non-secure disposal. Thus, the results from this study for a case study area could be safely applied to use in a real situation, in case values were based on assumption only. Therefore, to achieve these case study results, there is the responsibility of all concerned stakeholders to promote the disposal of these SFLs in an appropriate way so as to confirm that no SFLs leaked from the system inappropriately during disposal. However, if in the near future SFLs are still not being collected wholly to correct the disposal process with some SFLs leaking inappropriately during disposal, then users should know what the optimal way to manage these lamps is. Users can input the actual amount of SFLs collected into the model instead of using the last value to find out the new optimal SFLs recycling value, because this model was designed with flexibility for the user in order to change the amount of SFLs inputted.

Moreover, when considering the results obtained from the testing model in this case study area, the results indicated that the major source of the total environmental impact came from the transportation process. This point may imply the reason why the model selected to send SFLs generated from each source for disposal to the plants which were located nearest the site of the SFL generation source. For example, most of SFLs generated from Bangkok and Samuthprakarn were sent for recycling at R.P.1 which is located in Samuthprakarn, as well as, most of the SFLs generated from Pathumthani and Nonthaburi were sent for recycling at R.P.2 which is located in Pathumthani. At the same time, most of the SFLs generated from Samutsakhon and Nakhonpathom were sent for disposal at a non-recycling plant which is located at Ratchaburi. From these results, it may be concluded that the distance parameter had direct effects on the value of environmental impact. To observe these phenomena more closely, further detailed explanations provided for in the following pages may help to clarify.

Although the results in the previous conclusion indicated that the environmental impact would be reduced when rate of recycling is increased, the model still does not opt to send the SFLs generated from Samutsakhon and

Nakhonpathom for disposal at a recycling plant because the process integrates a longer distance. On the contrary, these lamps are still being disposed of at a non-recycling plant because it shows a shorter distance for transportation than that to a recycling site. Therefore, to further reduce the amount of environmental impact and achieve both a distance reduction and an increasing recycling rate, the addition of a new hypothetical recycling plant would be necessary instead of integrating the non-recycling plant at Ratchaburi province. However, if this improvement is inputted into model and the model can not compute a new scenario with the given constraints, it may ignore the new options and the decision maker would be back again at the first optimal decision for SFL recycling in this case study area.

The results of the output model data were explored by a sensitivity analysis of the model. The results showed that the optimum rate of recycling and the optimum capacity expansion was sensitive when the growth rate of SFLs, interest rate and inflation rate were changed. On the contrary, when the other model parameters such as the investment cost, operation and maintenance cost, recovery material price, and fuel price (which included the normalization and weight factors in the environmental impact assessment) were varied within the range of -100% to 100%, the decision variables were not directly affected.

Finally, the value of funds in the cost model for adding capacity was generally discontinuous, arising from a lumpy investment and a dimensionality of a decision space, as well as nonlinearity of objectives and constraints. These show the difficulties of the optimization tasks and the optimal solution cannot be guaranteed. To solve these problems, the first method selected to optimize the results of the frontline solver in this study was the evolutional method, available on the Frontline solver and MATLAB. However, because this model was too complex, after a trial run on a random search, the optimum results could not be logically illustrated. Alternately, in order to find the best possible way, the method was changed to GRG-nonlinear because it could help the user find the optimum solution in the trial with the initial value. Using this method, the initial value of the decision variables was trailed and the model runs were conducted until the optimum results were obtained.

7.2 The possibilities of future research work

In this study, the decision making model for SFL recycling was developed broadly. It was prepared to serve for the recycling of other wastes so as to find out the optimum alternatives for recycling by focusing on the environmental impacts generated during the life cycle. Therefore, it is possible for future researchers to modify this model to apply for finding out the optimum recycling options of other wastes such as electronic waste, in cooperating with the LCA. Also, the methodology that defined this research could be applied to further examine other possibilities. However, because of the lack of data, the case study area for this research was focused on only in Bangkok and the vicinity of the central part of Thailand. In response to the requirement of the recycling of SFLs in all of Thailand, future research may be done to cover the entire country.

However, to achieve both economic benefits and lessen the environmental impact, future researchers may develop this model additionally with multi-objective functions. The first objective would be to maximize the total benefits and to minimize costs, as well as to minimize the amount of environmental impact generated from the entire chain of activities involved with SFL recycling. Moreover, because of the complexity of the model, it was difficult to find an appropriate method to solve the problems. So, the next researcher may consider how to develop a more user-friendly model.

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APPENDICES

Appendix A

THE SEARCH FOR AN OFF-THE-SHELF SOLVER

The intention In the beginning of this study was to find a commercial solver that could automate solving the study model: i.e., a solver that could deal with a large-scale nonlinear discontinuous model with no convexity. The following is a summary review of optimization software products that are widely used.

The Off-the Shelf Solvers.

There are a number of off-the-shelf optimization solvers whose prices range from less than $20 up to several thousand dollars. These solvers may be categorized into three groups:

1. Optimization solvers for scientific projects such as MATLAB.
2. Optimization solvers for management planning (business/industry) such as LINDO/LINGO, What's Best!> CRYSTAL BALL (OPTQUEST). Frontline's Solvers, and ILOG.
3. Programming languages for optimization such as AMPL, OPL, CPLEX, GAMS/M1NOS.

MATLAB - is an interactive extensible modeling language, providing tools for high-performance numerical computation, advanced graphics, graphical user interface (GUI) building, and automated code generation. This software is well suited for scientific problems such as fuzzy logic control design, digital signal processing and communication, data acquisition. MATLAB currently also provides tools for Finance and economics analysis including bond and option pricing, yield and sensitivity analysis, portfolio optimization and analysis, asset allocation, *cash* flow analysis, risk management, forecasting and simulation, and Monte Carlo simulation. It also provides a toolbox for general large-scale optimization linear and non-linear programming, using classical optimization techniques such as a simplex method, a quasi-Newton algorithm, and sequential quadratic programming. These classical optimization techniques are myopic, and thus MATLAB is not well suited for the work in this study.

LINDO/LINGO - are easy interactive optimizers based upon script modeling languages, providing Dynamic Link Libraries (DLLs). LINDO can be used to solve linear and integer programming problems, allowing users to interface with MATLAB. while LINGO is a comprehensive tool designed for building and solving both linear and nonlinear as well as integer optimization models. LINDO and LINGO are well suited for the sort of modeling problems that are encountered in the areas of operations research such as linear programming, scheduling, and budgeting. LINDO is based upon a simplex method and branching and cut generation strategies- The problem in using these is that it is difficult to convert the study model to a linear problem because the utilization terms are discontinuous. To convert it to a continuous form, it would be necessary to create a set of dummy variables, such as the build and not build variables. This does not seem feasible because the utilization variables of the study model are not decision variables. A similar difficulty is encountered with discontinuity in QA' (treated flows). Although LINGO can solve nonlinear problems, it uses gradient search which makes it difficult to handle nonconvexity, as discussed above.

What's Best! - is a spreadsheet solver based upon MS Excel which, allows for solving linear and nonlinear problems with complex structures. But, for a nonlinear programming model, the technique used by What's Best! is based upon a generalized reduced gradient (GRG) algorithm, a Steepest Edge/Steepest Descent option, and sequential linear programming procedures, limitations, again in the nonconvex setting. Thus, for nonconvex programming problems, the solution obtained from such search methods depends on the starting point, and for a nonlinear nonconvex problem, we choose a number of starting solutions and choose the result, which is even then not guaranteed to be globally optimal. This makes computation very time consuming. especially for a large-scale nonlinear problem even though it allows for handling unlimited dimensions.

CRYSTAL BALL This is a widely used MS Excel Spreadsheet software package, capable of performing risk analysis and simulation forecasting. CRYSTAL BALL has also developed a global optimization solver, OPTQUEST, using heuristic Tabu Search, Neural Networks, and Scatter Search algorithms. The advantage of OPTQUEST is that it was developed to handle nonlinear difficulties involving finding local optimal solutions. Initially, this seemed promising for the study model. However, an evaluation of OPTQUEST in CRYSTAL BALL revealed that it was designed for quite specific structures, not allowing the user to supply complex constraints. The study model implicitly has such constraints.

Frontline's Solvers — are widely used spreadsheet solvers for large-scale linear and nonlinear, continuous and discontinuous problems. The advantage of Frontline's products is that they employ various technologies ranging from classical optimization tools such as the simplex method, Generalized Reduced Gradient, and the Lipschitz global optimization technique to heuristic 'search such as Genetic and Evolutionary Algorithms. These solvers are namely Standard LP/Quadratic, Standard GRG Nonlinear, Standard Evolutionary, Large-Scale Nonlinear, and LGO Global Optimizer. Frontline has currently integrated OPTQUEST into its capabilities, allowing for solving nonlinear discontinuous problems. OPTQUEST in Frontline is more flexible than that in CRYSTAL BALL, since it allows users to create models with any type of structures. For these reasons, Frontline's solvers such as large-scale GRG Nonlinear, LGO, Standard Evolutionary, and OPTQUEST seemed appropriate for the study model. These solvers were evaluated by trying both large and small-scale problems, and it was found that while some of these solvers may find correct solutions for a small nonlinear nonconvex problem, for a large-scale problem with nonconvexity, none of these produced a reasonable solution in a reasonable amount of time, as seen below.

ILOG/CPLEX - provides robust optimizers for solving linear, mixed-integer, and quadratic programming problems in mission-critical resource allocation applications. supply chain planning, telecommunication network design, transportation logistics, e-business, and finance. This is very expensive software widely used in large corporations such as Chrysler Corporation, AT&T, and Nokia.

In addition to the above solvers, there are other programming languages which allow users to write customized application programs for solving non-linear programming such as CAMS, MiNOS. The other modeling languages for optimization, that have been widely used in the development of several commercial solvers, are AMPL and OPL. These programming languages, which provide function libraries for optimization, are well suited for users who have proficiency in objected-oriented programming.

Appendix B

Eco-indicator 99 method, individualist version

Evaluation: "A" refers to the average weighting set. "I" refers to the weighting set belonging to the individualist perspective (recommended). The default Eco-indicator 99 method is the Hierarchist version with average weighting set (average of the full panel).

This V2 version is adapted for SimaPro 6.0. All characterisation factors in this method are entered for the 'unspecified' subcompartment of each compartment (Raw materials, air, water, soil) and thus applicable on all subcompartments, where no specific characterisation value is specified.

In case the original method only reported a characterisation value for one specific subcompartment, this value is taken as the characterisation value for all subcompartments in this compartment. In case two different characterisation values for emissions to agricultural and industrial soil are available, the value for industrial soil is taken as the characterisation value for all other subcompartments to soil.

Other adaptations (V2.1):

- Method expanded with all factors applied by ecoinvent (all categories), except for 'particulates >10 um' for respiratory damage
- Chromium/nickel factors for carcinogenics adapted (see ecoinvent)
- Factor '0' (zero) added for emssions to the 'long-term' subcompartment of air and water

Other adaptations (August 2004):

- Characterisation factors category Minerals: "Nickel, 1.13% in sulfides, 0.76% in crude ore, in ground"; "Nickel, 1.98% in silicates, 1.04% in crude ore, in ground"; "Zinc 9%, Lead 5%, in sulfide, in ground" updated, according to updated characterisation factors in EI99 for Nickel, in ore and Zinc, in ore.
- Characterisation factor category Respiratory inorganics added for Particulate matter, Particulate matter, unspecified and Particulates, > 2,5 um, and <10 um.

This method is NOT fully adapted for inventory data from the USA Input Output Database 98, and therefore omits emissions that could have been included in impact assessment.

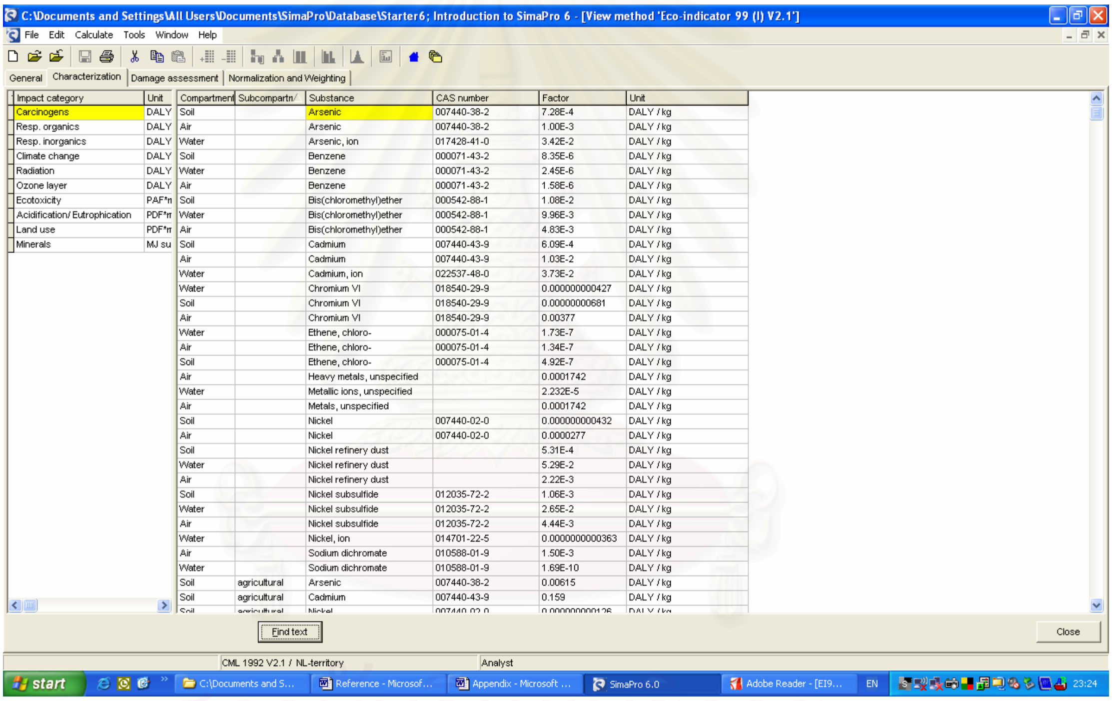
In the Eco-indicator 99 method normalisation and weighting are performed at damage category level (endpoint level in ISO terminology). There are three damage categories:

HH Human Health (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted)

EQ Ecosystem Quality (unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species)

R Resources (unit: MJ surplus energy Additional energy requirement to compensate lower future ore grade)

For database of on simapro are shown as follow

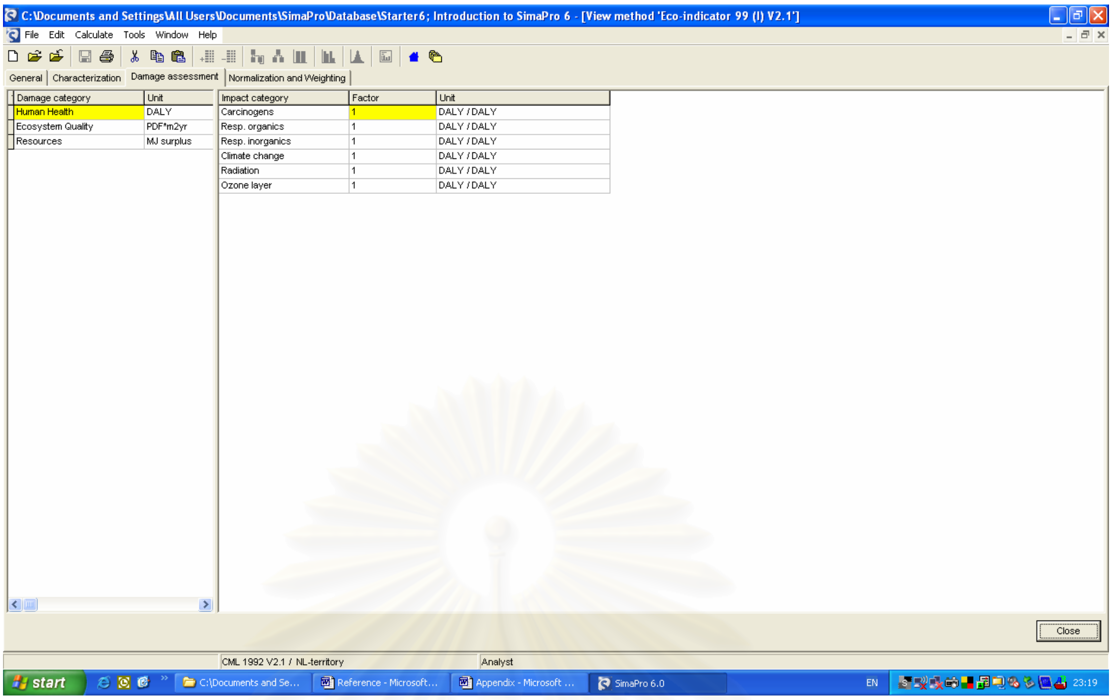


Impact category	Unit
Carcinogens	DALY
Resp. organics	DALY
Resp. inorganics	DALY
Climate change	DALY
Radiation	DALY
Ozone layer	DALY
Ecotoxicity	PAF*n
Acidification/ Eutrophication	PDF*n
Land use	PDF*n
Minerals	MJ su

Compartment	Subcompartn	Substance	CAS number	Factor	Unit
Soil		Arsenic	007440-38-2	7.28E-4	DALY / kg
Air		Arsenic	007440-38-2	1.00E-3	DALY / kg
Water		Arsenic, ion	017428-41-0	3.42E-2	DALY / kg
Soil		Benzene	000071-43-2	8.35E-6	DALY / kg
Water		Benzene	000071-43-2	2.45E-6	DALY / kg
Air		Benzene	000071-43-2	1.58E-6	DALY / kg
Soil		Bis(chloromethyl)ether	000542-88-1	1.08E-2	DALY / kg
Water		Bis(chloromethyl)ether	000542-88-1	9.96E-3	DALY / kg
Air		Bis(chloromethyl)ether	000542-88-1	4.83E-3	DALY / kg
Soil		Cadmium	007440-43-9	6.09E-4	DALY / kg
Air		Cadmium	007440-43-9	1.03E-2	DALY / kg
Water		Cadmium, ion	022537-48-0	3.73E-2	DALY / kg
Water		Chromium VI	018540-29-9	0.000000000427	DALY / kg
Soil		Chromium VI	018540-29-9	0.00000000681	DALY / kg
Air		Chromium VI	018540-29-9	0.00377	DALY / kg
Water		Ethene, chloro-	000075-01-4	1.73E-7	DALY / kg
Air		Ethene, chloro-	000075-01-4	1.34E-7	DALY / kg
Soil		Ethene, chloro-	000075-01-4	4.92E-7	DALY / kg
Air		Heavy metals, unspecified		0.0001742	DALY / kg
Water		Metallic ions, unspecified		2.232E-5	DALY / kg
Air		Metals, unspecified		0.0001742	DALY / kg
Soil		Nickel	007440-02-0	0.000000000432	DALY / kg
Air		Nickel	007440-02-0	0.0000277	DALY / kg
Soil		Nickel refinery dust		5.31E-4	DALY / kg
Water		Nickel refinery dust		5.29E-2	DALY / kg
Air		Nickel refinery dust		2.22E-3	DALY / kg
Soil		Nickel subsulfide	012035-72-2	1.06E-3	DALY / kg
Water		Nickel subsulfide	012035-72-2	2.65E-2	DALY / kg
Air		Nickel subsulfide	012035-72-2	4.44E-3	DALY / kg
Water		Nickel, ion	014701-22-5	0.0000000000363	DALY / kg
Air		Sodium dichromate	010588-01-9	1.50E-3	DALY / kg
Water		Sodium dichromate	010588-01-9	1.69E-10	DALY / kg
Soil	agricultural	Arsenic	007440-38-2	0.00615	DALY / kg
Soil	agricultural	Cadmium	007440-43-9	0.159	DALY / kg

Eco-indicator 99 has a damage assessment step. This means that the impact category indicator results that are calculated in the Characterisation step are added to form damage categories. Addition without weighting is justified here because all impact categories that refer to the same damage type (like human health) have the same unit (for instance DALY). This procedure can also be interpreted as grouping.

The damage categories (and not the impact categories) are normalised on an European level (damage caused by 1 European per year), mostly based on 1993 as base year, with some updates for the most important emissions. Please note that the normalisation set is dependent on the perspective chosen.

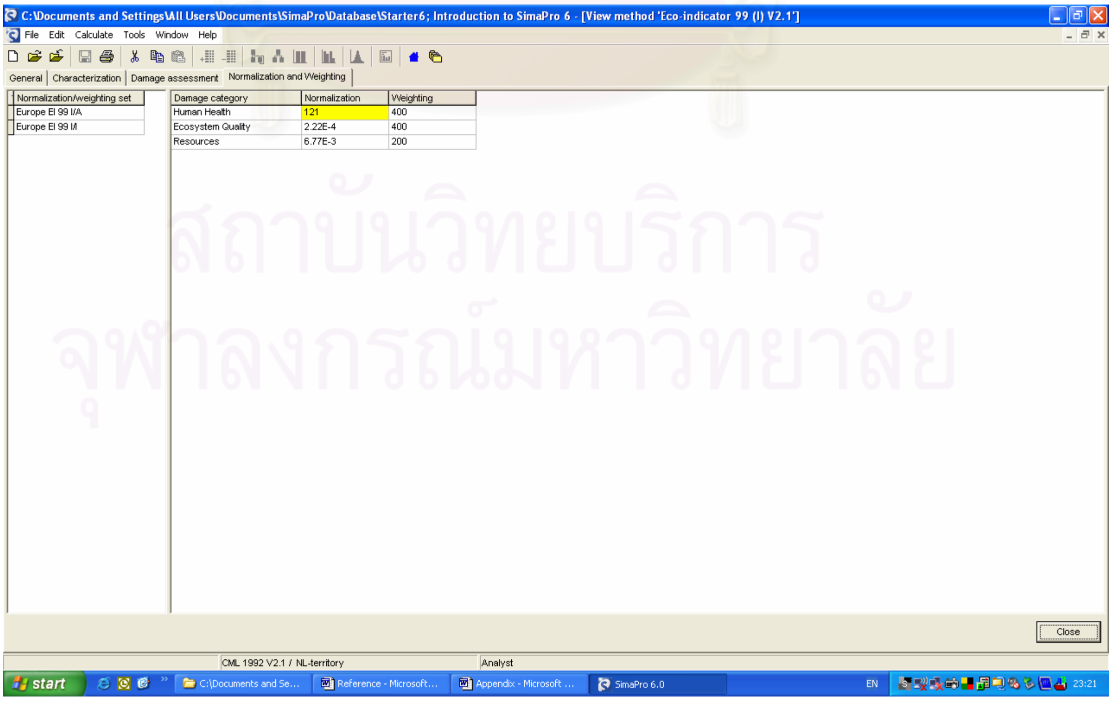


Damage category	Unit
Human Health	DALY
Ecosystem Quality	PDF*m2yr
Resources	MJ surplus

Impact category	Factor	Unit
Carcinogens	1	DALY / DALY
Resp. organics	1	DALY / DALY
Resp. inorganics	1	DALY / DALY
Climate change	1	DALY / DALY
Radiation	1	DALY / DALY
Ozone layer	1	DALY / DALY

CML 1992 V2.1 / NL-territory
Analyst

The normalised damage categories can also be used with the triangle tool. This is very useful if two products are to be compared without weighting, in case the damage indicators for Product A and B are conflicting (A is higher on Human health and B is higher on Ecosystem Quality). In such a case the answer is dependent on the weighting factors for Ecosystem quality, Resources and Human health.



Normalization/weighting set
Europe EI 99 I/A
Europe EI 99 I/I

Damage category	Normalization	Weighting
Human Health	121	400
Ecosystem Quality	2.22E-4	400
Resources	6.77E-3	200

CML 1992 V2.1 / NL-territory
Analyst

The triangle must be understood as a way to show all possible combinations of weighting factors (represented as a percentage in such a way that they add up to 100%). If damage categories have conflicting values, the triangle will display two area's. One area represents all weighting sets for which product A has a lower environmental load, the other area will represent all weighting sets for which B has a lower load than A. The line in between is the line of indifference. These are the weighting sets for which the environmental load of A and B are the same.

The benefit of using the triangle is that you do not always need to know which exact weighting set you want to use. The stakeholders only have to decide in which area (on which side of the line of indifference) the weighting set may be. See also help file

Uncertainties

Of course it is very important to pay attention to the uncertainties in the methodology. We distinguish two types:

- Data uncertainties
- Uncertainties about the correctness of the models used

Data uncertainties are specified for most damage factors as squared geometric standard deviation in the original reports, but not in the software. It is not useful to express the uncertainties of the model as a distribution. Uncertainties about the model are related to subjective choices in the model. In order to deal with them we developed three different versions of the methodology, using the archetypes specified in the

- Egalitarian perspective
- Hierarchist perspective
- Individualist perspective.

In the individualist perspective the chosen time perspective is short term (100 years or less), Substances are included if there is complete proof regarding their effect. For example, only proven carcinogenic substances in IARC class 1 included, while classes 2a, 2b and 3 have deliberately been excluded. In the individualist perspective damages are assumed to be recoverable by technological and economic development. In the case of fossil fuels the assumption is made that fossil fuels cannot really be depleted. Therefore they are left out in weighting. In the DALY calculations age weighting is included.

For further inforation see the Eco-indicator 99 reports, available from our web site www.pre.nl Due to adjustments of the method and/or inventory data sets the Eco-indicator 95 in SimaPro might not give the same result as the printed version.

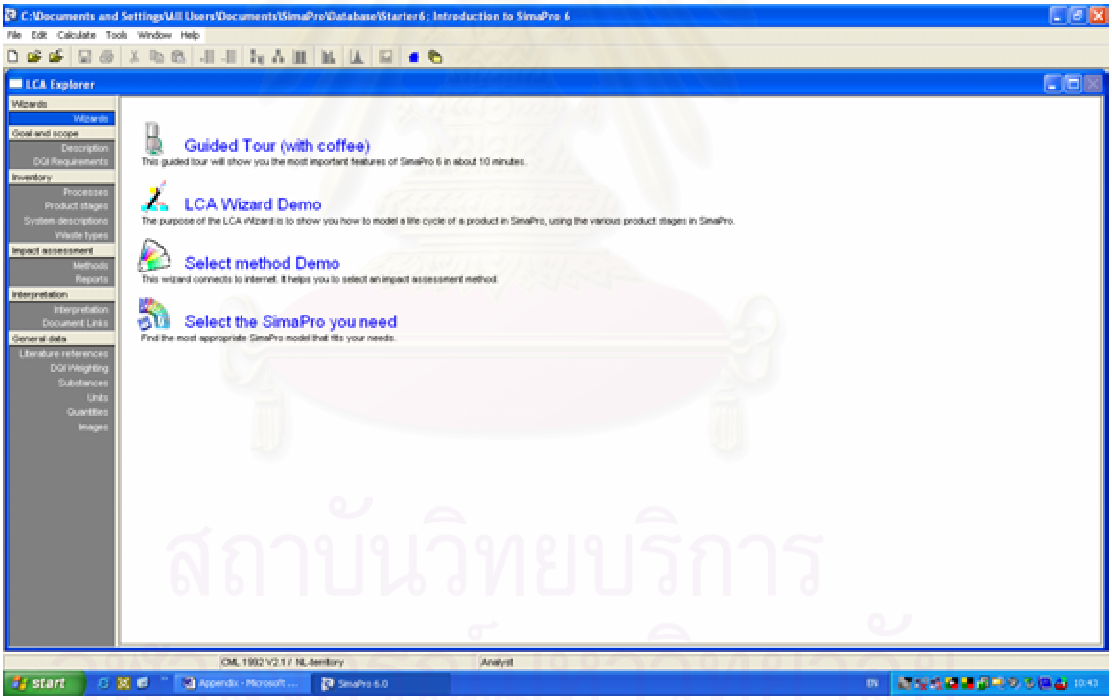
Appendix C

Software tool for LCA

A lot of software tool for life cycle assessment are presented on the market as shown in comparing table of software for environmental impact assessment on next page.

For this study, some database of model process is referred from Simapro 6.0 Demo Version. This part of appendix will refer the some parts of this demo as following.

The main worksheet of this version is composed of many categories as shown in following figure. On this worksheet, the user can accesses to the required data and trial for formulation of life cycle of each product to assess the impact that happened as step by step through other worksheets by click at LCA wizard demo. However, for more detail, the user can contact the host directly by e-mail.



This guided tour will show you the most important features of SimaPro 6 in about 10 minutes.

The purpose of the LCA Wizard is to show you how to model a life cycle of a product in SimaPro, using the various product stages in SimaPro.

This wizard connects to internet. It helps you to select an impact assessment method.

Find the most appropriate SimaPro model that fits your needs.

Comparing Table of Software for Environmental Impact Assessment

Categories	CUMPAN 1.44	ECO-it 1.0	EDIP PC-tool	EPS 4.0 Design System	Gabi3	SimaPro 4.0	TEAM	Umberto 3.5
Country	Germany	Netherland	Denmark	Sweden	Germany	Netherland	France	Germany
Number of sold license	62	70	100	>200	250	>600	>200	>350
Price on year 2000	$6,000	$215	$700	$3,200	$2,500-8,000	S2,540	$3,200	$1,000-20,000
Time of study	1 day	<2 hours	<l week	<l week	*<1 month*	<1 day	<1 day	<1 week
Method to assess the impact	Several	All single score method	EDIP, enviromental method	EPS	Eco Indicator	E195,EI99,EPS7,CML,EDIP,EPS	CML. EPA, IPCC, CVCH	Eco indicator, Swiss, Eco-point
<u>Standard</u>								
ISO 14040	x	-	x	x	x	x	x	x
results are shown in table form	x	x	x	x	x	x	x	*x*
results are shown in graph	x	x	x	x	x	x	x	x
Improvement of data	by yearly	other time	other time	yearly	other time	twice yearly	yearly	other time

x = detected , - = non-detected

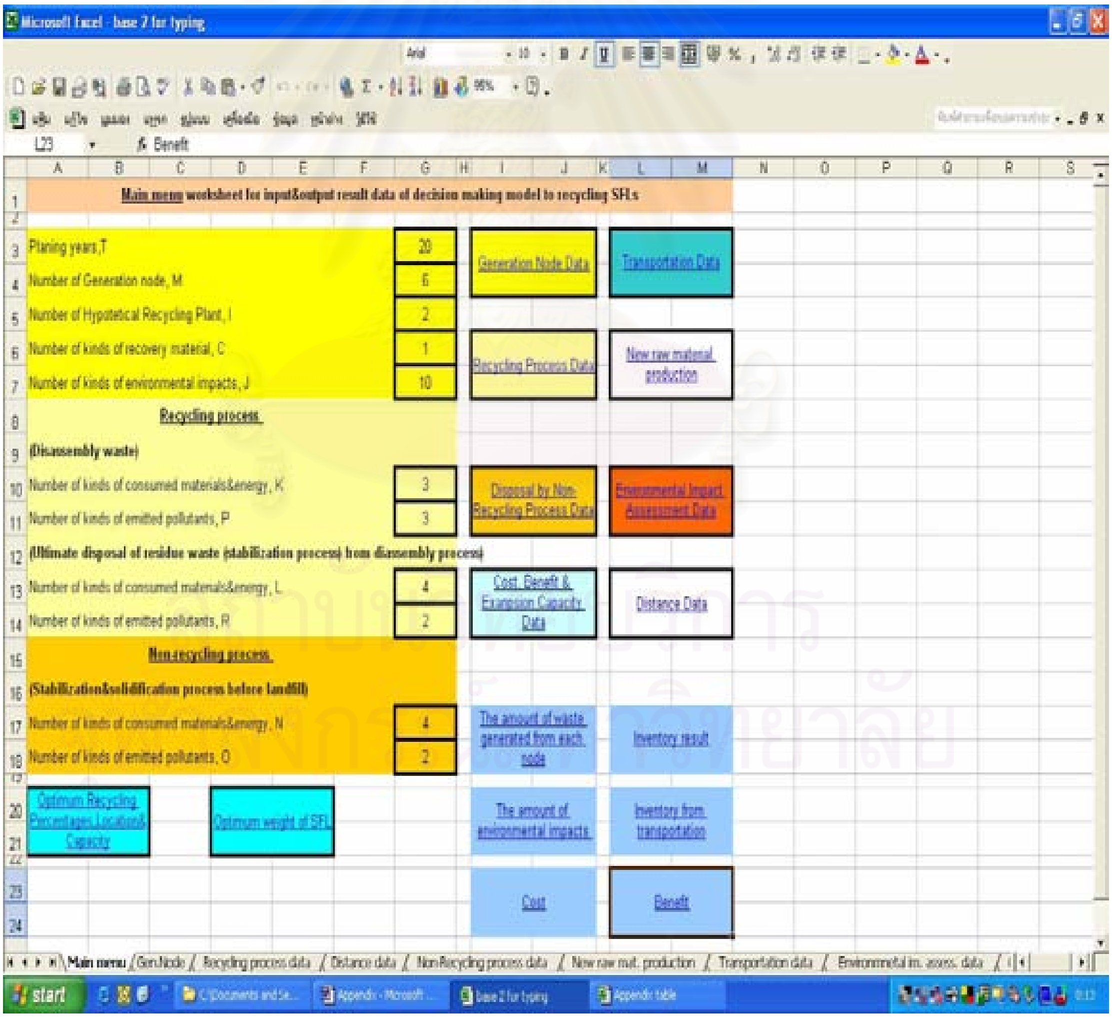
Appendix D

Manual of Decision making model for recycling SFLs

This section is the explanation of manual of decision making model for recycling SFLs which formulated on excel spreadsheet and optimized by using frontline solve program especially for this research.

The interface of this model is started at main menu data worksheet which user can input the required parameter data and find out the output data of solving by click at presented button on interface designed such as generation node data, recycling process data, non-recycling process data etc. In the same time, main input data such as the number of generation node, planning year are also required as shown in following.

Main menu data worksheet.



Main menu worksheet for input&output result data of decision making model to recycling SFLs

Planing years,T: 20
Number of Generation node, M: 6
Number of Hypotetical Recycling Plant, I: 2
Number of kinds of recovery material, C: 1
Number of kinds of environmental impacts, J: 10

Recycling process

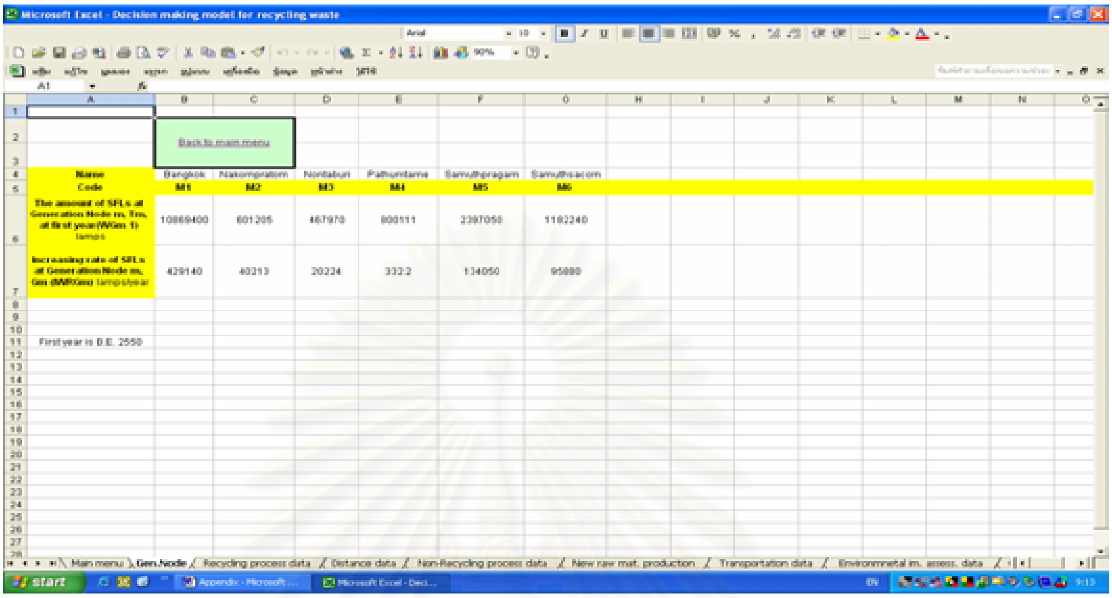
(Disassembly waste)
Number of kinds of consumed materials&energy, K: 3
Number of kinds of emitted pollutants, P: 3

(Ultimate disposal of residue waste (stabilization process) from disassembly process)
Number of kinds of consumed materials&energy, L: 4
Number of kinds of emitted pollutants, R: 2

Non-recycling process

(Stabilization&solidification process before landfill)
Number of kinds of consumed materials&energy, N: 4
Number of kinds of emitted pollutants, O: 2

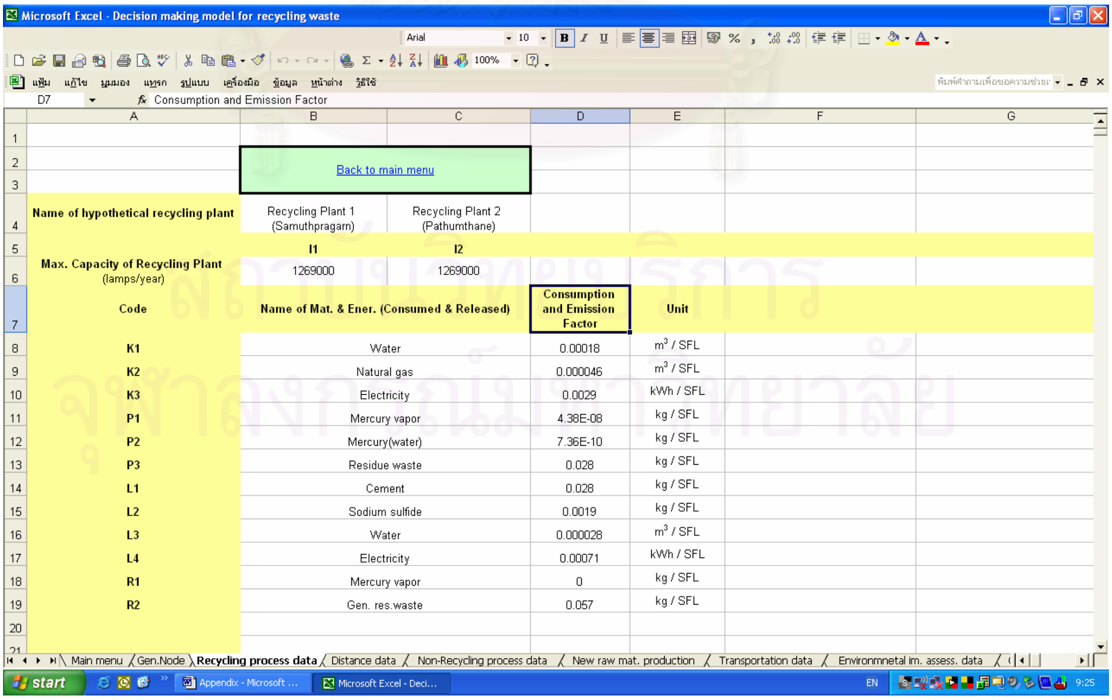
After the main input data such as the number of generation node and others are inputted in the main menu worksheet already and the generation node button is clicked, the program will move to generation node data worksheet as show in following. On this worksheet, the name and the initial loads of generation loads of each province including with growth rate are inputted.



Name	Bangkok	Nakornpratom	Nontaburi	Pathumtame	Samuthpragam	Samuthsacom
Code	M1	M2	M3	M4	M5	M6
The amount of SFLs at Generation Node m, Tm, at first year(WGm 1) lamps	10869400	601205	467970	800111	2397050	1182240
Increasing rate of SFLs at Generation Node m, Gm (BARGm) lamps/year	429140	40313	20234	3332	134050	95880

First year is B.E. 2550

After there, clicking at back to main menu button, program will move to main menu worksheet again. Then, the next required input data is inputted by clinking at the other input button, for example, the material and energy consumption including with the pollutant emission at recycling process data are inputted after clicking at recycling process data botton as shown in following

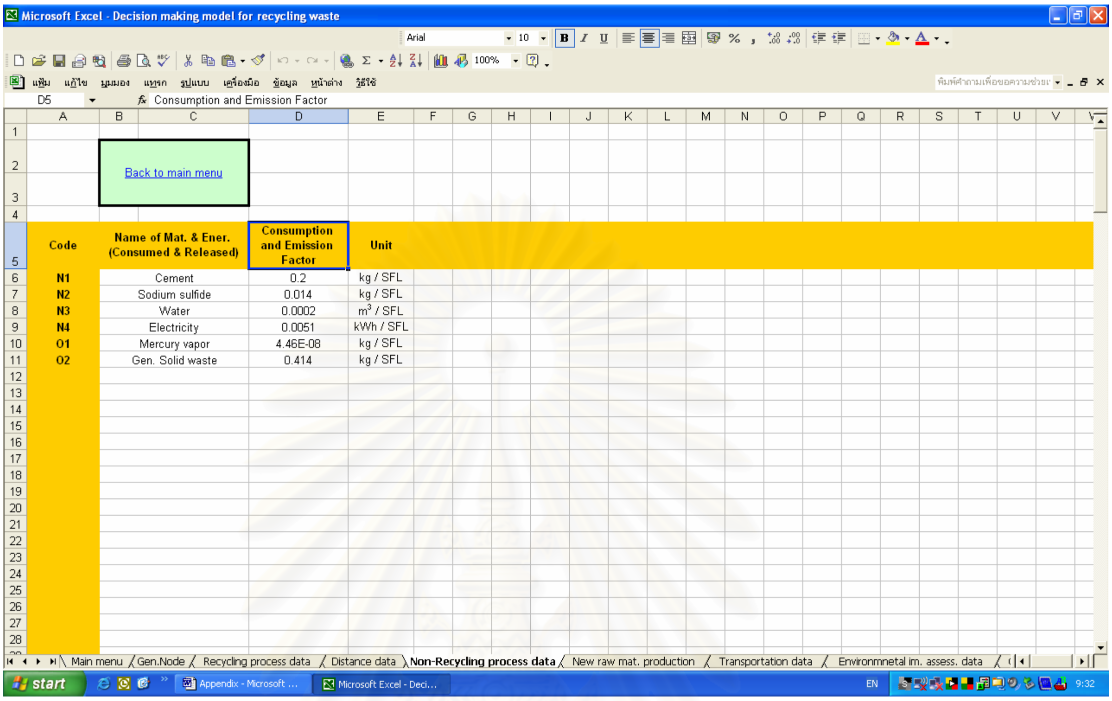


D7: Consumption and Emission Factor

Name of hypothetical recycling plant	Recycling Plant 1 (Samuthpragam)	Recycling Plant 2 (Pathumthane)		
	I1	I2		
Max. Capacity of Recycling Plant (lamps/year)	1269000	1269000		
Code	Name of Mat. & Ener. (Consumed & Released)		Consumption and Emission Factor	Unit
K1	Water		0.00018	m^3 / SFL
K2	Natural gas		0.000046	m^3 / SFL
K3	Electricity		0.0029	kWh / SFL
P1	Mercury vapor		4.38E-08	kg / SFL
P2	Mercury(water)		7.36E-10	kg / SFL
P3	Residue waste		0.028	kg / SFL
L1	Cement		0.028	kg / SFL
L2	Sodium sulfide		0.0019	kg / SFL
L3	Water		0.000028	m^3 / SFL
L4	Electricity		0.00071	kWh / SFL
R1	Mercury vapor		0	kg / SFL
R2	Gen. res.waste		0.057	kg / SFL

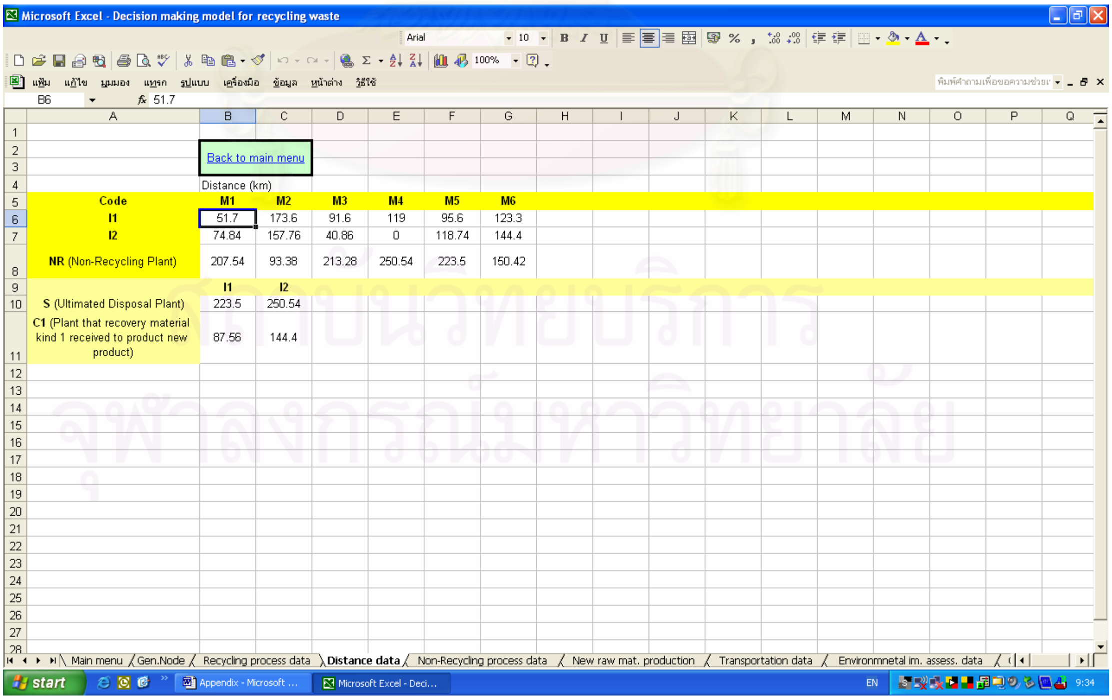
As the last step, the procedure is reversed again and all required data are inputted on each input data worksheet by clinking at button that need to input data on main menu worksheet. The all of these input data worksheet are shown as following, step by step.

Worksheet for the required input data at non-recycling process as shown in following.



Code	Name of Mat. & Ener. (Consumed & Released)	Consumption and Emission Factor	Unit
N1	Cement	0.2	kg / SFL
N2	Sodium sulfide	0.014	kg / SFL
N3	Water	0.0002	m^3 / SFL
N4	Electricity	0.0051	kWh / SFL
O1	Mercury vapor	4.46E-08	kg / SFL
O2	Gen. Solid waste	0.414	kg / SFL

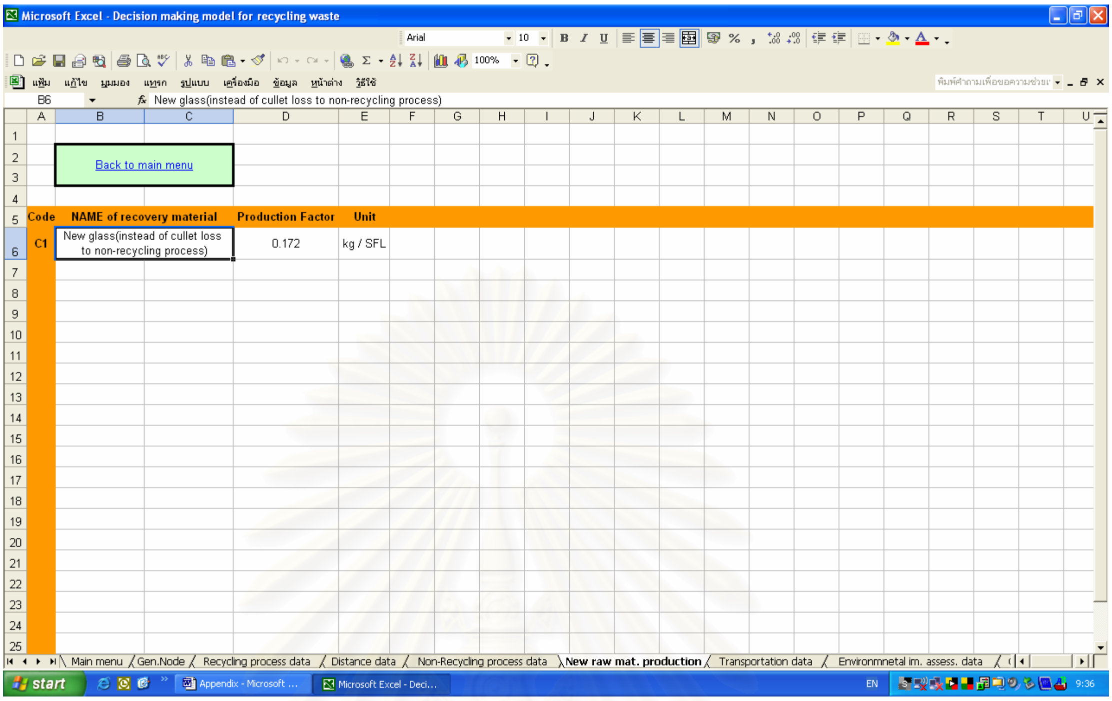
Worksheet for distance data of transportation between each node are shown in following.



Distance (km)

Code	M1	M2	M3	M4	M5	M6
I1	51.7	173.6	91.6	119	95.6	123.3
I2	74.84	157.76	40.86	0	118.74	144.4
NR (Non-Recycling Plant)	207.54	93.38	213.28	250.54	223.5	150.42
	I1	**I2**				
S (Ultimated Disposal Plant)	223.5	250.54				
C1 (Plant that recovery material kind 1 received to product new product)	87.56	144.4				

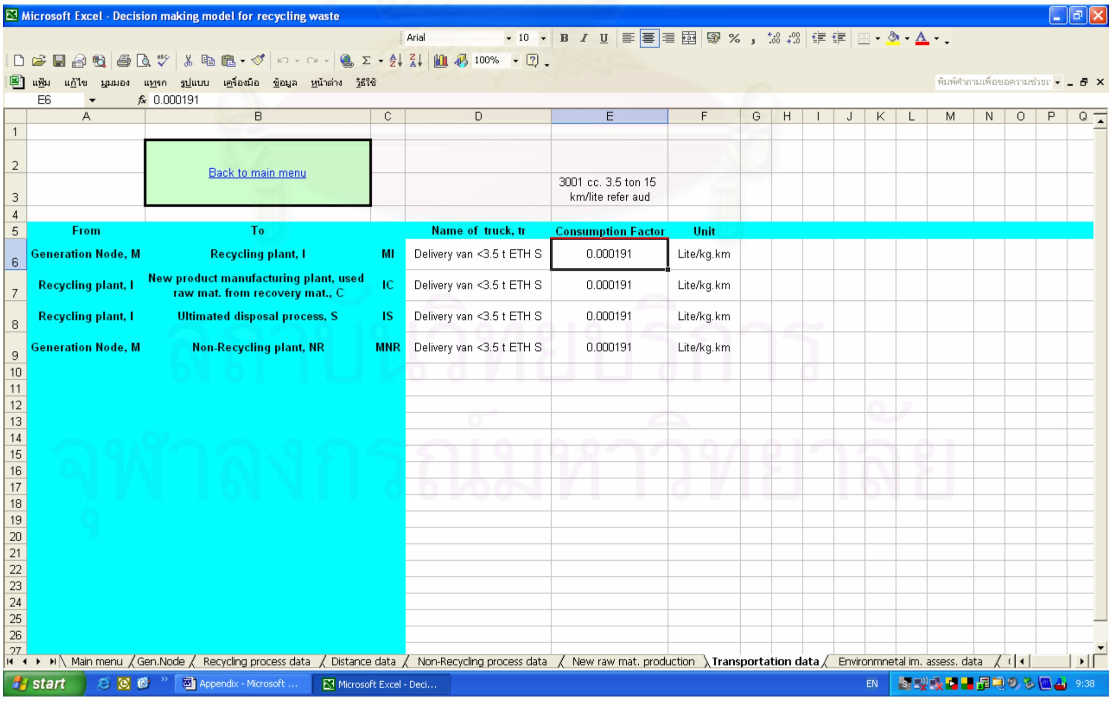
Worksheet for new raw material production instead of loss of recovery material are shown in following.



B6 New glass(instead of cullet loss to non-recycling process)

Code	NAME of recovery material	Production Factor	Unit
C1	New glass(instead of cullet loss to non-recycling process)	0.172	kg / SFL

Worksheet for transportation data which the fuel consumption is inputted as shown in following.

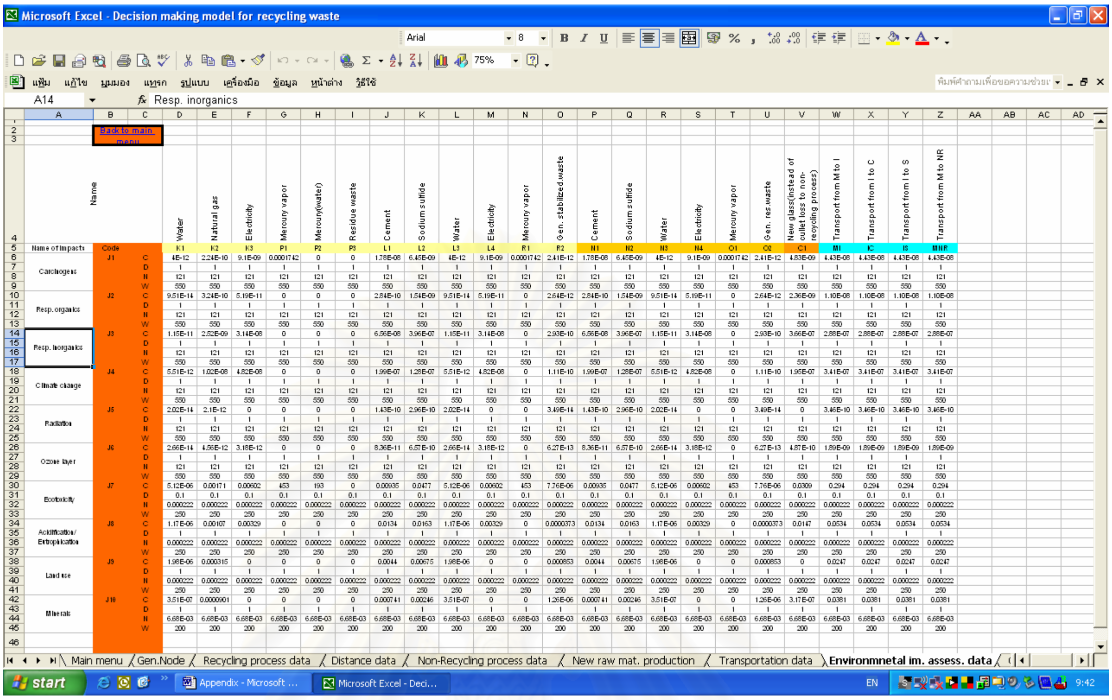


E6 0.000191

3001 cc. 3.5 ton 15 km/lite refer aud

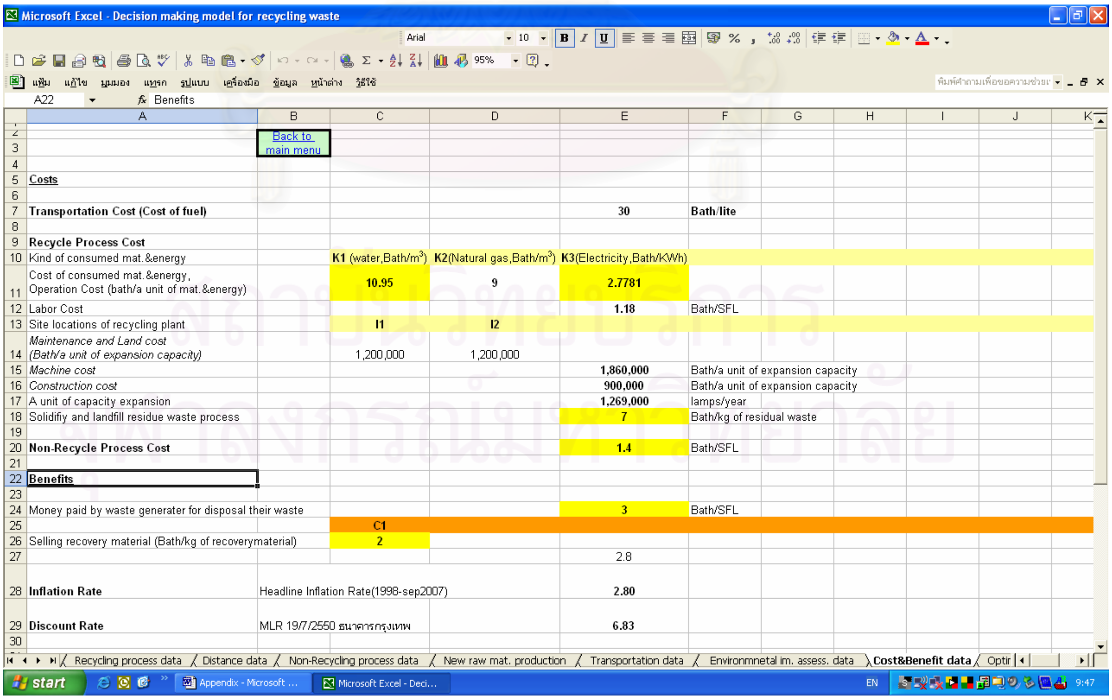
From	To		Name of truck, tr	Consumption Factor	Unit
Generation Node, M	Recycling plant, I	MI	Delivery van <3.5 t ETH S	0.000191	Lite/kg.km
Recycling plant, I	New product manufacturing plant, used raw mat. from recovery mat., C	IC	Delivery van <3.5 t ETH S	0.000191	Lite/kg.km
Recycling plant, I	Ultimated disposal process, S	IS	Delivery van <3.5 t ETH S	0.000191	Lite/kg.km
Generation Node, M	Non-Recycling plant, NR	MNR	Delivery van <3.5 t ETH S	0.000191	Lite/kg.km

Worksheet for environmental impact assessment data which are the characterization factor, the damage assessment factor, the normalization factor and weighting factor as shown in following.



Name			Water	Natural gas	Electricity	Mercury vapor	Mercury(water)	Residue waste	Cement	Sodium sulfide	Water	Electricity	Mercury vapor	Gen. stabilized.waste	Cement	Sodium sulfide	Water	Electricity	Mercury vapor	Gen. res.waste	New glass(instead of cullet loss to non-recycling process)	Transport from M to I	Transport from I to C	Transport from I to S	Transport from M to NR
Name of Impacts	Code		K1	K2	K3	P1	P2	P3	L1	L2	L3	L4	R1	R2	N1	N2	N3	N4	O1	O2	C1	MI	IC	IS	MNR
Carcinogens	J1	C	4E-12	2.24E-10	9.1E-09	0.0001742	0	0	1.78E-08	6.45E-09	4E-12	9.1E-09	0.0001742	2.41E-12	1.78E-08	6.45E-09	4E-12	9.1E-09	0.0001742	2.41E-12	4.83E-09	4.43E-08	4.43E-08	4.43E-08	4.43E-08
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121
		W	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550
Resp. organics	J2	C	9.51E-14	3.24E-10	5.19E-11	0	0	0	2.84E-10	1.54E-09	9.51E-14	5.19E-11	0	2.64E-12	2.84E-10	1.54E-09	9.51E-14	5.19E-11	0	2.64E-12	2.36E-09	1.10E-08	1.10E-08	1.10E-08	1.10E-08
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121
		W	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550
Resp. inorganics	J3	C	1.15E-11	2.52E-09	3.14E-08	0	0	0	6.56E-08	3.96E-07	1.15E-11	3.14E-08	0	2.93E-10	6.56E-08	3.96E-07	1.15E-11	3.14E-08	0	2.93E-10	3.66E-07	2.88E-07	2.88E-07	2.88E-07	2.88E-07
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121
		W	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550
Climate change	J4	C	5.51E-12	1.02E-08	4.82E-08	0	0	0	1.99E-07	1.28E-07	5.51E-12	4.82E-08	0	1.11E-10	1.99E-07	1.28E-07	5.51E-12	4.82E-08	0	1.11E-10	1.95E-07	3.41E-07	3.41E-07	3.41E-07	3.41E-07
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121
		W	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550
Radiation	J5	C	2.02E-14	2.1E-12	0	0	0	0	1.43E-10	2.96E-10	2.02E-14	0	0	3.49E-14	1.43E-10	2.96E-10	2.02E-14	0	0	3.49E-14	0	3.46E-10	3.46E-10	3.46E-10	3.46E-10
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121
		W	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550
Ozone layer	J6	C	2.66E-14	4.56E-12	3.18E-12	0	0	0	8.36E-11	6.57E-10	2.66E-14	3.18E-12	0	6.27E-13	8.36E-11	6.57E-10	2.66E-14	3.18E-12	0	6.27E-13	4.87E-10	1.89E-09	1.89E-09	1.89E-09	1.89E-09
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121	121
		W	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550
Ecotoxicity	J7	C	5.12E-06	0.00171	0.00602	453	193	0	0.00935	0.0477	5.12E-06	0.00602	453	7.76E-06	0.00935	0.0477	5.12E-06	0.00602	453	7.76E-06	0.0309	0.294	0.294	0.294	0.294
		D	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
		N	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222
		W	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Acidification/ Eutrophication	J8	C	1.17E-06	0.00107	0.00329	0	0	0	0.0134	0.0163	1.17E-06	0.00329	0	0.0000373	0.0134	0.0163	1.17E-06	0.00329	0	0.0000373	0.0147	0.0534	0.0534	0.0534	0.0534
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222
		W	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Land use	J9	C	1.98E-06	0.000315	0	0	0	0	0.0044	0.00675	1.98E-06	0	0	0.000853	0.0044	0.00675	1.98E-06	0	0	0.000853	0	0.0247	0.0247	0.0247	0.0247
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222	0.000222
		W	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250
Minerals	J10	C	3.51E-07	0.0000901	0	0	0	0	0.000741	0.00246	3.51E-07	0	0	1.26E-06	0.000741	0.00246	3.51E-07	0	0	1.26E-06	3.17E-07	0.0381	0.0381	0.0381	0.0381
		D	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		N	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03	6.68E-03
		W	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

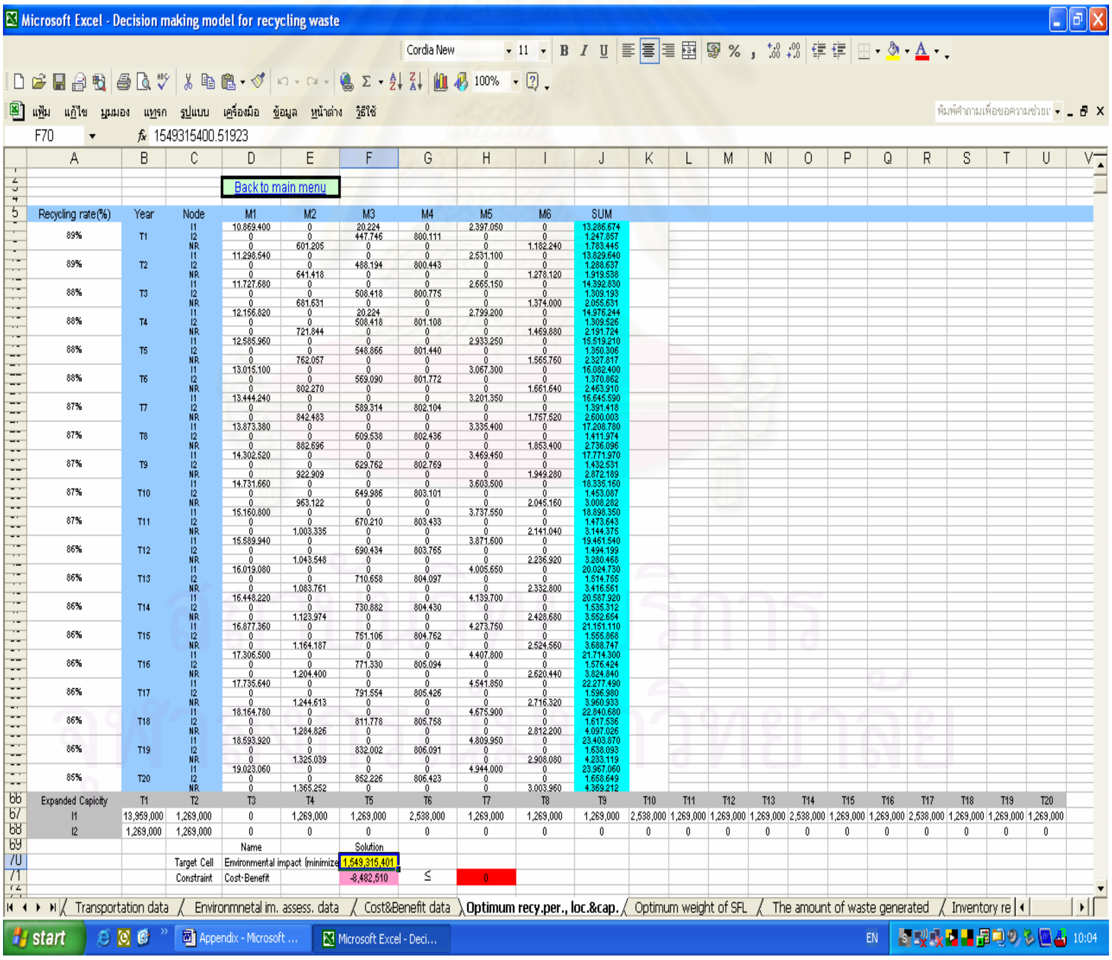
Worksheet for cost and benefit data which are for example the investment cost, operation cost, labor cost, the disposal fee and recovery material price including with interest rate(discount rate) and inflation rate as shown in following.



A	B	C	D	E	F
Costs					
Transportation Cost (Cost of fuel)				**30**	**Bath/lite**
Recycle Process Cost					
Kind of consumed mat.&energy		**K1** (water,Bath/m³)	**K2**(Natural gas,Bath/m³)	**K3**(Electricity,Bath/KWh)	
Cost of consumed mat.&energy, Operation Cost (bath/a unit of mat.&energy)		**10.95**	**9**	**2.7781**	
Labor Cost				**1.18**	Bath/SFL
Site locations of recycling plant		**I1**	**I2**		
Maintenance and Land cost (Bath/a unit of expansion capacity)		1,200,000	1,200,000		
Machine cost				**1,860,000**	Bath/a unit of expansion capacity
Construction cost				**900,000**	Bath/a unit of expansion capacity
A unit of capacity expansion				**1,269,000**	lamps/year
Solidifiy and landfill residue waste process				**7**	Bath/kg of residual waste
Non-Recycle Process Cost				**1.4**	Bath/SFL
Benefits					
Money paid by waste generater for disposal their waste				**3**	Bath/SFL
		C1			
Selling recovery material (Bath/kg of recoverymaterial)		**2**			
				2.8	
Inflation Rate	Headline Inflation Rate(1998-sep2007)			**2.80**	
Discount Rate	MLR 19/7/2550 ธนาคารกรุงเทพ			**6.83**	

After all required input data are already input in this model, the output results are shown as two options. First one is the optimum recycling percentage (rate) and optimum capacity at each location each year. When this output data worksheet is opened, the decision making will be done by using frontline solver program and optimum results of decision making including with the value of environmental impact which are minimized will be shown out on this worksheet. Also, the optimum weight of waste that decided to recycle at each generation in each year of planning. These output data worksheet is accessed by click at optimum result at main menu worksheet button which located on the left hand site of main menu data worksheet as shown in following.

Worksheet of the optimum recycling percentage (rate) and optimum capacity at each location each year.



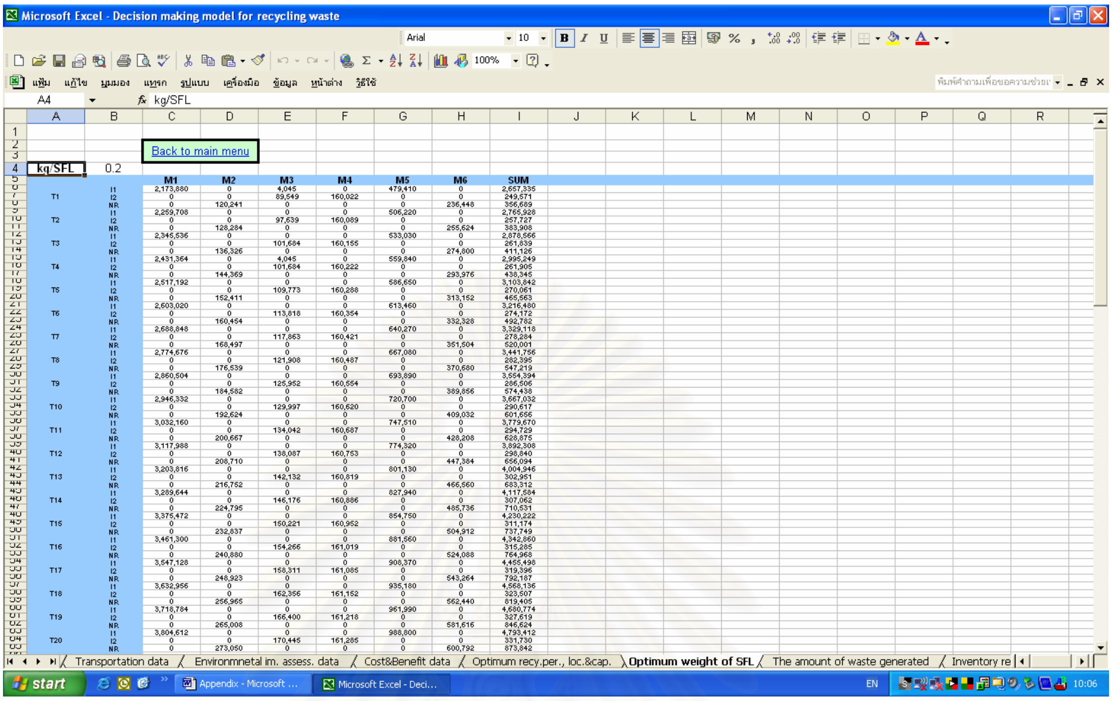
fx 1549315400.51923

Recycling rate(%)	Year	Node	M1	M2	M3	M4	M5	M6	SUM
89%	T1	I1	10.869.400	0	20.224	0	2.397.050	0	13.286.674
		I2	0	0	447.746	800.111	0	0	1.247.857
		NR	0	601.205	0	0	0	1.182.240	1.783.445
89%	T2	I1	11.298.540	0	0	0	2.531.100	0	13.829.640
		I2	0	0	488.194	800.443	0	0	1.288.637
		NR	0	641.418	0	0	0	1.278.120	1.919.538
88%	T3	I1	11.727.680	0	0	0	2.665.150	0	14.392.830
		I2	0	0	508.418	800.775	0	0	1.309.193
		NR	0	681.631	0	0	0	1.374.000	2.055.631
88%	T4	I1	12.156.820	0	20.224	0	2.799.200	0	14.976.244
		I2	0	0	508.418	801.108	0	0	1.309.526
		NR	0	721.844	0	0	0	1.469.880	2.191.724
88%	T5	I1	12.585.960	0	0	0	2.933.250	0	15.519.210
		I2	0	0	548.866	801.440	0	0	1.350.306
		NR	0	762.057	0	0	0	1.565.760	2.327.817
88%	T6	I1	13.015.100	0	0	0	3.067.300	0	16.082.400
		I2	0	0	569.090	801.772	0	0	1.370.862
		NR	0	802.270	0	0	0	1.661.640	2.463.910
87%	T7	I1	13.444.240	0	0	0	3.201.350	0	16.645.590
		I2	0	0	589.314	802.104	0	0	1.391.418
		NR	0	842.483	0	0	0	1.757.520	2.600.003
87%	T8	I1	13.873.380	0	0	0	3.335.400	0	17.208.780
		I2	0	0	609.538	802.436	0	0	1.411.974
		NR	0	882.696	0	0	0	1.853.400	2.736.096
87%	T9	I1	14.302.520	0	0	0	3.469.450	0	17.771.970
		I2	0	0	629.762	802.769	0	0	1.432.531
		NR	0	922.909	0	0	0	1.949.280	2.872.189
87%	T10	I1	14.731.660	0	0	0	3.603.500	0	18.335.160
		I2	0	0	649.986	803.101	0	0	1.453.087
		NR	0	963.122	0	0	0	2.045.160	3.008.282
87%	T11	I1	15.160.800	0	0	0	3.737.550	0	18.898.350
		I2	0	0	670.210	803.433	0	0	1.473.643
		NR	0	1.003.335	0	0	0	2.141.040	3.144.375
86%	T12	I1	15.589.940	0	0	0	3.871.600	0	19.461.540
		I2	0	0	690.434	803.765	0	0	1.494.199
		NR	0	1.043.548	0	0	0	2.236.920	3.280.468
86%	T13	I1	16.019.080	0	0	0	4.005.650	0	20.024.730
		I2	0	0	710.658	804.097	0	0	1.514.755
		NR	0	1.083.761	0	0	0	2.332.800	3.416.561
86%	T14	I1	16.448.220	0	0	0	4.139.700	0	20.587.920
		I2	0	0	730.882	804.430	0	0	1.535.312
		NR	0	1.123.974	0	0	0	2.428.680	3.552.654
86%	T15	I1	16.877.360	0	0	0	4.273.750	0	21.151.110
		I2	0	0	751.106	804.762	0	0	1.555.868
		NR	0	1.164.187	0	0	0	2.524.560	3.688.747
86%	T16	I1	17.306.500	0	0	0	4.407.800	0	21.714.300
		I2	0	0	771.330	805.094	0	0	1.576.424
		NR	0	1.204.400	0	0	0	2.620.440	3.824.840
86%	T17	I1	17.735.640	0	0	0	4.541.850	0	22.277.490
		I2	0	0	791.554	805.426	0	0	1.596.980
		NR	0	1.244.613	0	0	0	2.716.320	3.960.933
86%	T18	I1	18.164.780	0	0	0	4.675.900	0	22.840.680
		I2	0	0	811.778	805.758	0	0	1.617.536
		NR	0	1.284.826	0	0	0	2.812.200	4.097.026
86%	T19	I1	18.593.920	0	0	0	4.809.950	0	23.403.870
		I2	0	0	832.002	806.091	0	0	1.638.093
		NR	0	1.325.039	0	0	0	2.908.080	4.233.119
85%	T20	I1	19.023.060	0	0	0	4.944.000	0	23.967.060
		I2	0	0	852.226	806.423	0	0	1.658.649
		NR	0	1.365.252	0	0	0	3.003.960	4.369.212

Expanded Capicity	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
I1	13,959,000	1,269,000	0	1,269,000	1,269,000	2,538,000	1,269,000	1,269,000	1,269,000	2,538,000	1,269,000	1,269,000	1,269,000	2,538,000	1,269,000	1,269,000	2,538,000	1,269,000	1,269,000	1,269,000
I2	1,269,000	1,269,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	Name	Solution		
Target Cell	Environmental impact (minimize	1,549,315,401		
Constraint	Cost-Benefit	-8,482,510	≤	0

Worksheet of the optimum weight of waste that decided to recycle at each generation in each year of planning.



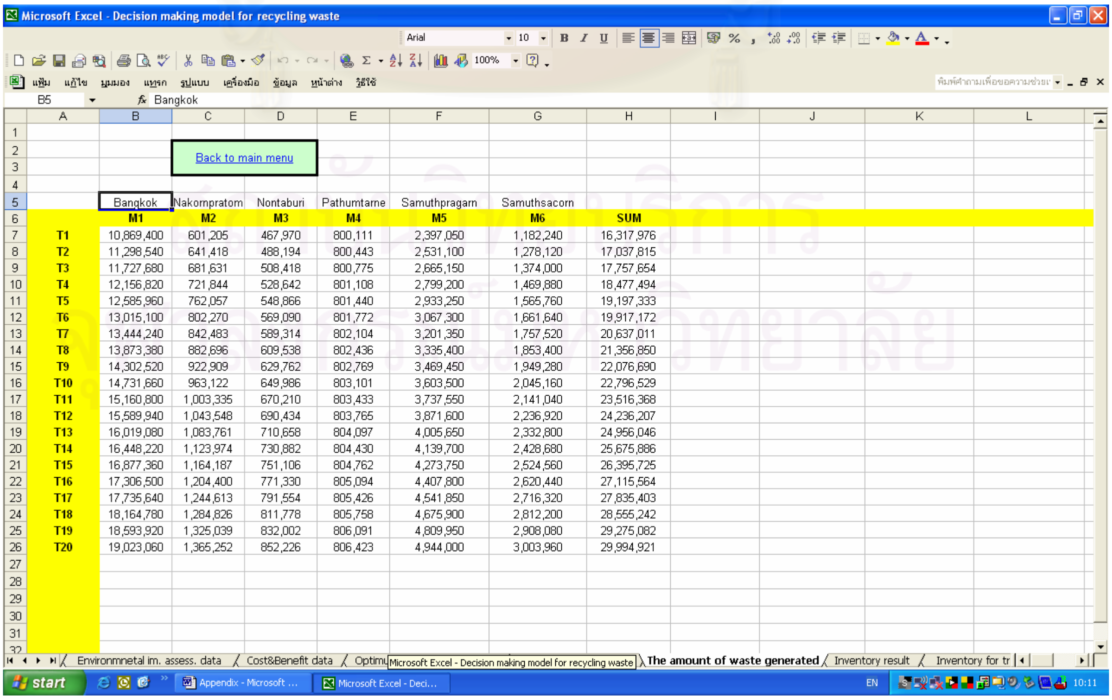
A4 kg/SFL

kg/SFL 0.2

		M1	M2	M3	M4	M5	M6	SUM
T1	I1	2,173,880	0	4,045	0	479,410	0	2,657,335
	I2	0	0	89,549	160,022	0	0	249,571
	NR	0	120,241	0	0	0	236,448	356,689
T2	I1	2,259,708	0	0	0	506,220	0	2,765,928
	I2	0	0	97,639	160,089	0	0	257,727
	NR	0	128,284	0	0	0	255,624	383,908
T3	I1	2,345,536	0	0	0	533,030	0	2,878,566
	I2	0	0	101,684	160,155	0	0	261,839
	NR	0	136,326	0	0	0	274,800	411,126
T4	I1	2,431,364	0	4,045	0	559,840	0	2,995,249
	I2	0	0	101,684	160,222	0	0	261,905
	NR	0	144,369	0	0	0	293,976	438,345
T5	I1	2,517,192	0	0	0	586,650	0	3,103,842
	I2	0	0	109,773	160,288	0	0	270,061
	NR	0	152,411	0	0	0	313,152	465,563
T6	I1	2,603,020	0	0	0	613,460	0	3,216,480
	I2	0	0	113,818	160,354	0	0	274,172
	NR	0	160,454	0	0	0	332,328	492,782
T7	I1	2,688,848	0	0	0	640,270	0	3,329,118
	I2	0	0	117,863	160,421	0	0	278,284
	NR	0	168,497	0	0	0	351,504	520,001
T8	I1	2,774,676	0	0	0	667,080	0	3,441,756
	I2	0	0	121,908	160,487	0	0	282,395
	NR	0	176,539	0	0	0	370,680	547,219
T9	I1	2,860,504	0	0	0	693,890	0	3,554,394
	I2	0	0	125,952	160,554	0	0	286,506
	NR	0	184,582	0	0	0	389,856	574,438
T10	I1	2,946,332	0	0	0	720,700	0	3,667,032
	I2	0	0	129,997	160,620	0	0	290,617
	NR	0	192,624	0	0	0	409,032	601,656
T11	I1	3,032,160	0	0	0	747,510	0	3,779,670
	I2	0	0	134,042	160,687	0	0	294,729
	NR	0	200,667	0	0	0	428,208	628,875
T12	I1	3,117,988	0	0	0	774,320	0	3,892,308
	I2	0	0	138,087	160,753	0	0	298,840
	NR	0	208,710	0	0	0	447,384	656,094
T13	I1	3,203,816	0	0	0	801,130	0	4,004,946
	I2	0	0	142,132	160,819	0	0	302,951
	NR	0	216,752	0	0	0	466,560	683,312
T14	I1	3,289,644	0	0	0	827,940	0	4,117,584
	I2	0	0	146,176	160,886	0	0	307,062
	NR	0	224,795	0	0	0	485,736	710,531
T15	I1	3,375,472	0	0	0	854,750	0	4,230,222
	I2	0	0	150,221	160,952	0	0	311,174
	NR	0	232,837	0	0	0	504,912	737,749
T16	I1	3,461,300	0	0	0	881,560	0	4,342,860
	I2	0	0	154,266	161,019	0	0	315,285
	NR	0	240,880	0	0	0	524,088	764,968
T17	I1	3,547,128	0	0	0	908,370	0	4,455,498
	I2	0	0	158,311	161,085	0	0	319,396
	NR	0	248,923	0	0	0	543,264	792,187
T18	I1	3,632,956	0	0	0	935,180	0	4,568,136
	I2	0	0	162,356	161,152	0	0	323,507
	NR	0	256,965	0	0	0	562,440	819,405
T19	I1	3,718,784	0	0	0	961,990	0	4,680,774
	I2	0	0	166,400	161,218	0	0	327,619
	NR	0	265,008	0	0	0	581,616	846,624
T20	I1	3,804,612	0	0	0	988,800	0	4,793,412
	I2	0	0	170,445	161,285	0	0	331,730
	NR	0	273,050	0	0	0	600,792	873,842

Second option of optimum results, this program is also designed to show the results of inventory analysis, environmental impact assessment, and cost and benefit results including with the amount of waste generated from each node.

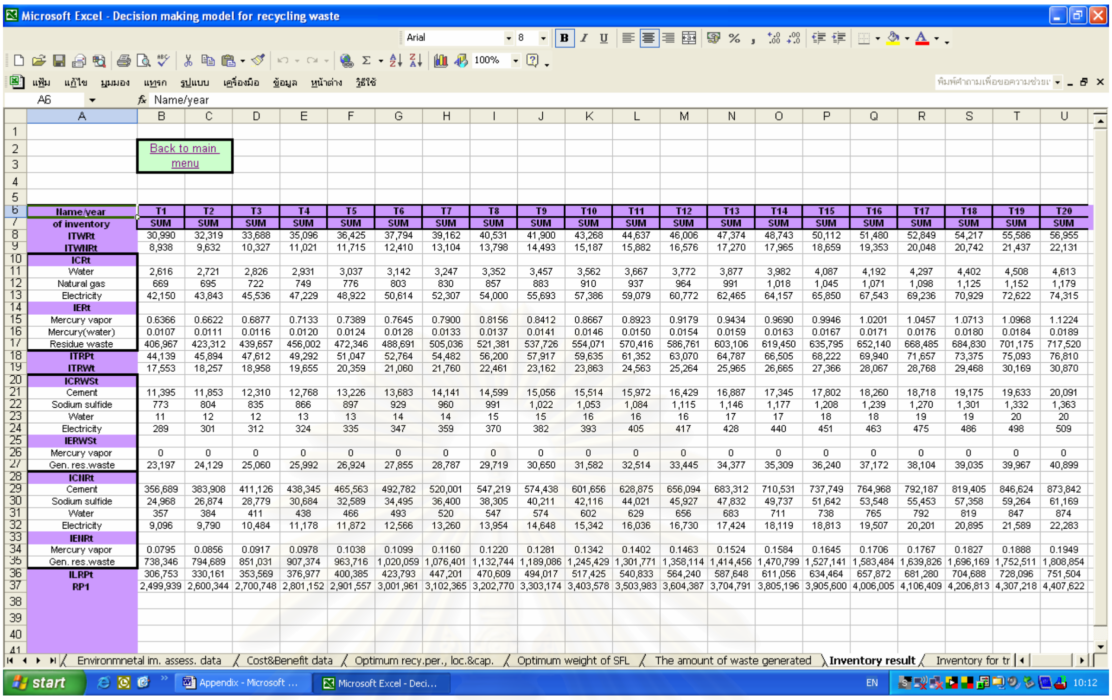
The amount of predicted waste generation.



B5 Bangkok

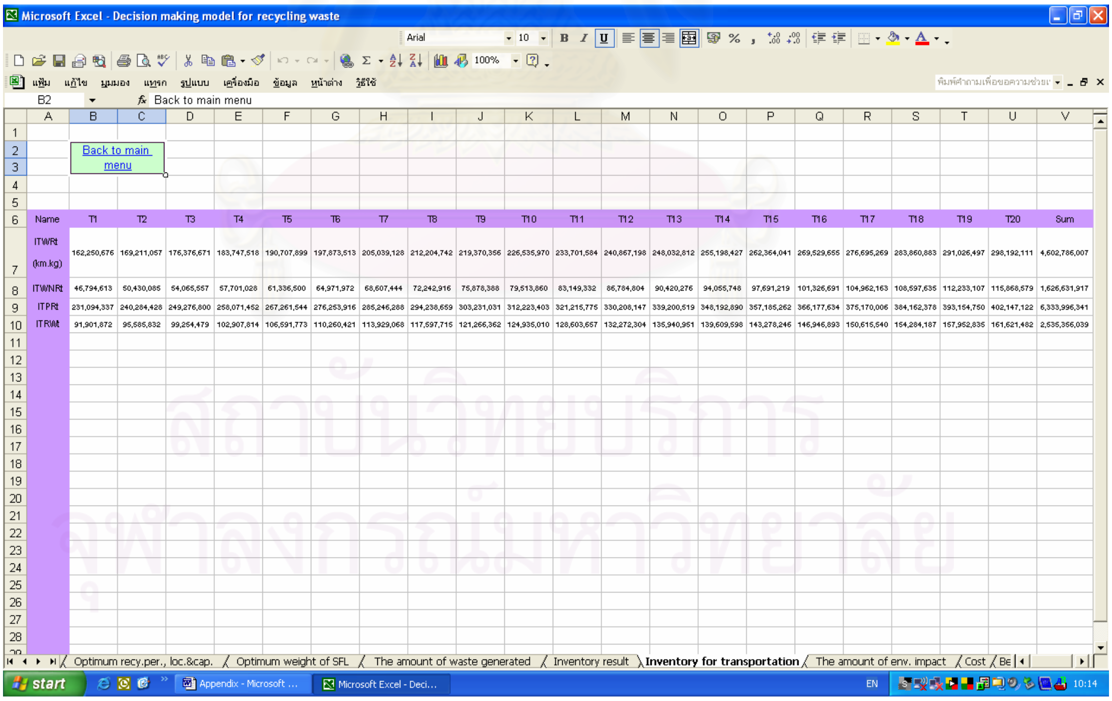
	Bangkok	Nakornpratom	Nontaburi	Pathumtarne	Samuthpragarn	Samuthsacorn	
	M1	M2	M3	M4	M5	M6	SUM
T1	10,869,400	601,205	467,970	800,111	2,397,050	1,182,240	16,317,976
T2	11,298,540	641,418	488,194	800,443	2,531,100	1,278,120	17,037,815
T3	11,727,680	681,631	508,418	800,775	2,665,150	1,374,000	17,757,654
T4	12,156,820	721,844	528,642	801,108	2,799,200	1,469,880	18,477,494
T5	12,585,960	762,057	548,866	801,440	2,933,250	1,565,760	19,197,333
T6	13,015,100	802,270	569,090	801,772	3,067,300	1,661,640	19,917,172
T7	13,444,240	842,483	589,314	802,104	3,201,350	1,757,520	20,637,011
T8	13,873,380	882,696	609,538	802,436	3,335,400	1,853,400	21,356,850
T9	14,302,520	922,909	629,762	802,769	3,469,450	1,949,280	22,076,690
T10	14,731,660	963,122	649,986	803,101	3,603,500	2,045,160	22,796,529
T11	15,160,800	1,003,335	670,210	803,433	3,737,550	2,141,040	23,516,368
T12	15,589,940	1,043,548	690,434	803,765	3,871,600	2,236,920	24,236,207
T13	16,019,080	1,083,761	710,658	804,097	4,005,650	2,332,800	24,956,046
T14	16,448,220	1,123,974	730,882	804,430	4,139,700	2,428,680	25,675,886
T15	16,877,360	1,164,187	751,106	804,762	4,273,750	2,524,560	26,395,725
T16	17,306,500	1,204,400	771,330	805,094	4,407,800	2,620,440	27,115,564
T17	17,735,640	1,244,613	791,554	805,426	4,541,850	2,716,320	27,835,403
T18	18,164,780	1,284,826	811,778	805,758	4,675,900	2,812,200	28,555,242
T19	18,593,920	1,325,039	832,002	806,091	4,809,950	2,908,080	29,275,082
T20	19,023,060	1,365,252	852,226	806,423	4,944,000	3,003,960	29,994,921

Inventory results happened from optimum in decision.



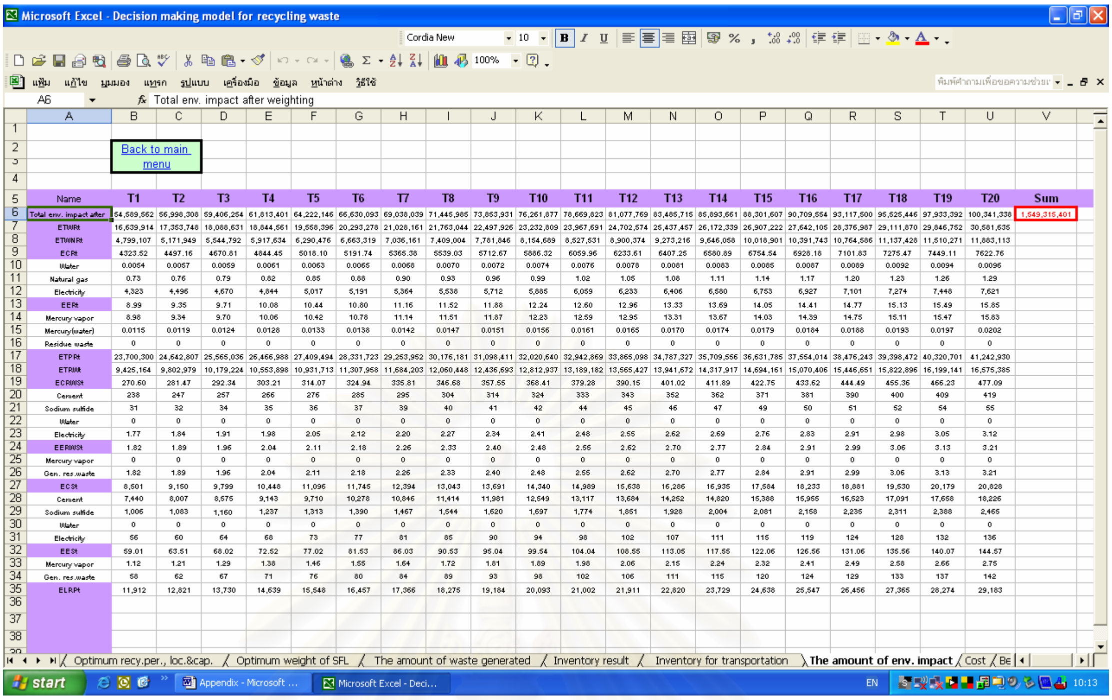
Name/year	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
of inventory	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM	SUM
ITWRt	30,990	32,319	33,688	35,096	36,425	37,794	39,162	40,531	41,900	43,268	44,637	46,006	47,374	48,743	50,112	51,480	52,849	54,217	55,586	56,955
ITWNRt	8,938	9,632	10,327	11,021	11,715	12,410	13,104	13,798	14,493	15,187	15,882	16,576	17,270	17,965	18,659	19,353	20,048	20,742	21,437	22,131
ICRt																				
Water	2,616	2,721	2,826	2,931	3,037	3,142	3,247	3,352	3,457	3,562	3,667	3,772	3,877	3,982	4,087	4,192	4,297	4,402	4,508	4,613
Natural gas	669	695	722	749	776	803	830	857	883	910	937	964	991	1,018	1,045	1,071	1,098	1,125	1,152	1,179
Electricity	42,150	43,843	45,536	47,229	48,922	50,614	52,307	54,000	55,693	57,386	59,079	60,772	62,465	64,157	65,850	67,543	69,236	70,929	72,622	74,315
IERt																				
Mercury vapor	0.6366	0.6622	0.6877	0.7133	0.7389	0.7645	0.7900	0.8156	0.8412	0.8667	0.8923	0.9179	0.9434	0.9690	0.9946	1.0201	1.0457	1.0713	1.0968	1.1224
Mercury(water)	0.0107	0.0111	0.0116	0.0120	0.0124	0.0128	0.0133	0.0137	0.0141	0.0146	0.0150	0.0154	0.0159	0.0163	0.0167	0.0171	0.0176	0.0180	0.0184	0.0189
Residue waste	406,967	423,312	439,657	456,002	472,346	488,691	505,036	521,381	537,726	554,071	570,416	586,761	603,106	619,450	635,795	652,140	668,485	684,830	701,175	717,520
ITRPt	44,139	45,894	47,612	49,292	51,047	52,764	54,482	56,200	57,917	59,635	61,352	63,070	64,787	66,505	68,222	69,940	71,657	73,375	75,093	76,810
ITRWt	17,553	18,257	18,958	19,655	20,359	21,060	21,760	22,461	23,162	23,863	24,563	25,264	25,965	26,665	27,366	28,067	28,768	29,468	30,169	30,870
ICRWSt																				
Cement	11,395	11,853	12,310	12,768	13,226	13,683	14,141	14,599	15,056	15,514	15,972	16,429	16,887	17,345	17,802	18,260	18,718	19,175	19,633	20,091
Sodium sulfide	773	804	835	866	897	929	960	991	1,022	1,053	1,084	1,115	1,146	1,177	1,208	1,239	1,270	1,301	1,332	1,363
Water	11	12	12	13	13	14	14	15	15	16	16	16	17	17	18	18	19	19	20	20
Electricity	289	301	312	324	335	347	359	370	382	393	405	417	428	440	451	463	475	486	498	509
IERWSt																				
Mercury vapor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gen. res.waste	23,197	24,129	25,060	25,992	26,924	27,855	28,787	29,719	30,650	31,582	32,514	33,445	34,377	35,309	36,240	37,172	38,104	39,035	39,967	40,899
ICNRt																				
Cement	356,689	383,908	411,126	438,345	465,563	492,782	520,001	547,219	574,438	601,656	628,875	656,094	683,312	710,531	737,749	764,968	792,187	819,405	846,624	873,842
Sodium sulfide	24,968	26,874	28,779	30,684	32,589	34,495	36,400	38,305	40,211	42,116	44,021	45,927	47,832	49,737	51,642	53,548	55,453	57,358	59,264	61,169
Water	357	384	411	438	466	493	520	547	574	602	629	656	683	711	738	765	792	819	847	874
Electricity	9,096	9,790	10,484	11,178	11,872	12,566	13,260	13,954	14,648	15,342	16,036	16,730	17,424	18,119	18,813	19,507	20,201	20,895	21,589	22,283
IENRt																				
Mercury vapor	0.0795	0.0856	0.0917	0.0978	0.1038	0.1099	0.1160	0.1220	0.1281	0.1342	0.1402	0.1463	0.1524	0.1584	0.1645	0.1706	0.1767	0.1827	0.1888	0.1949
Gen. res.waste	738,346	794,689	851,031	907,374	963,716	1,020,059	1,076,401	1,132,744	1,189,086	1,245,429	1,301,771	1,358,114	1,414,456	1,470,799	1,527,141	1,583,484	1,639,826	1,696,169	1,752,511	1,808,854
ILRPt	306,753	330,161	353,569	376,977	400,385	423,793	447,201	470,609	494,017	517,425	540,833	564,240	587,648	611,056	634,464	657,872	681,280	704,688	728,096	751,504
RP1	2,499,939	2,600,344	2,700,748	2,801,152	2,901,557	3,001,961	3,102,365	3,202,770	3,303,174	3,403,578	3,503,983	3,604,387	3,704,791	3,805,196	3,905,600	4,006,005	4,106,409	4,206,813	4,307,218	4,407,622

Inventory results which shown loads of transportation happened from optimum in decision.



Name	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	Sum
ITWRt (km.kg)	162,250,676	169,211,057	176,376,671	183,747,518	190,707,899	197,873,513	205,039,128	212,204,742	219,370,356	226,535,970	233,701,584	240,867,198	248,032,812	255,198,427	262,364,041	269,529,655	276,695,269	283,860,883	291,026,497	298,192,111	4,602,786,007
ITWNRt	46,794,613	50,430,085	54,065,557	57,701,028	61,336,500	64,971,972	68,607,444	72,242,916	75,878,388	79,513,860	83,149,332	86,784,804	90,420,276	94,055,748	97,691,219	101,326,691	104,962,163	108,597,635	112,233,107	115,868,579	1,626,631,917
ITPRt	231,094,337	240,284,428	249,276,800	258,071,452	267,261,544	276,253,916	285,246,288	294,238,659	303,231,031	312,223,403	321,215,775	330,208,147	339,200,519	348,192,890	357,185,262	366,177,634	375,170,006	384,162,378	393,154,750	402,147,122	6,333,996,341
ITRWt	91,901,872	95,585,832	99,254,479	102,907,814	106,591,773	110,260,421	113,929,068	117,597,715	121,266,362	124,935,010	128,603,657	132,272,304	135,940,951	139,609,598	143,278,246	146,946,893	150,615,540	154,284,187	157,952,835	161,621,482	2,535,356,039

The amount of environmental impact happened from optimum in decision.

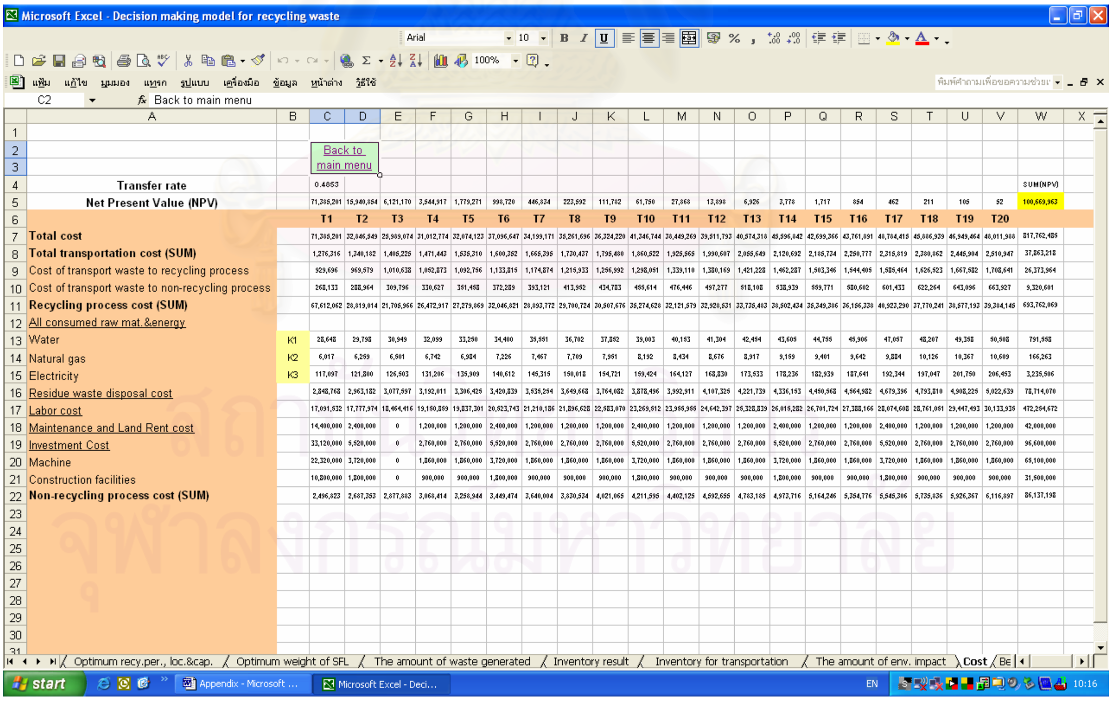


A6 Total env. impact after weighting

Name	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Total env. impact after	54,589,562	56,998,308	59,406,254	61,813,401	64,222,146	66,630,093	69,038,039	71,445,985	73,853,931	76,261,877
ETWRt	16,639,914	17,353,748	18,088,631	18,844,561	19,558,396	20,293,278	21,028,161	21,763,044	22,497,926	23,232,809
ETWNRt	4,799,107	5,171,949	5,544,792	5,917,634	6,290,476	6,663,319	7,036,161	7,409,004	7,781,846	8,154,689
ECRt	4323.52	4497.16	4670.81	4844.45	5018.10	5191.74	5365.38	5539.03	5712.67	5886.32
Water	0.0054	0.0057	0.0059	0.0061	0.0063	0.0065	0.0068	0.0070	0.0072	0.0074
Natural gas	0.73	0.76	0.79	0.82	0.85	0.88	0.90	0.93	0.96	0.99
Electricity	4,323	4,496	4,670	4,844	5,017	5,191	5,364	5,538	5,712	5,885
EERt	8.99	9.35	9.71	10.08	10.44	10.80	11.16	11.52	11.88	12.24
Mercury vapor	8.98	9.34	9.70	10.06	10.42	10.78	11.14	11.51	11.87	12.23
Mercury(water)	0.0115	0.0119	0.0124	0.0128	0.0133	0.0138	0.0142	0.0147	0.0151	0.0156
Residue waste	0	0	0	0	0	0	0	0	0	0
ETPRt	23,700,300	24,642,807	25,565,036	26,466,988	27,409,494	28,331,723	29,253,952	30,176,181	31,098,411	32,020,640
ETRWt	9,425,164	9,802,979	10,179,224	10,553,898	10,931,713	11,307,958	11,684,203	12,060,448	12,436,693	12,812,937
ECRWSt	270.60	281.47	292.34	303.21	314.07	324.94	335.81	346.68	357.55	368.41
Cement	238	247	257	266	276	285	295	304	314	324
Sodium sulfide	31	32	34	35	36	37	39	40	41	42
Water	0	0	0	0	0	0	0	0	0	0
Electricity	1.77	1.84	1.91	1.98	2.05	2.12	2.20	2.27	2.34	2.41
EERWSt	1.82	1.89	1.96	2.04	2.11	2.18	2.26	2.33	2.40	2.48
Mercury vapor	0	0	0	0	0	0	0	0	0	0
Gen. res.waste	1.82	1.89	1.96	2.04	2.11	2.18	2.26	2.33	2.40	2.48
ECSt	8,501	9,150	9,799	10,448	11,096	11,745	12,394	13,043	13,691	14,340
Cement	7,440	8,007	8,575	9,143	9,710	10,278	10,846	11,414	11,981	12,549
Sodium sulfide	1,006	1,083	1,160	1,237	1,313	1,390	1,467	1,544	1,620	1,697
Water	0	0	0	0	0	0	0	0	0	0
Electricity	56	60	64	68	73	77	81	85	90	94
EESt	59.01	63.51	68.02	72.52	77.02	81.53	86.03	90.53	95.04	99.54
Mercury vapor	1.12	1.21	1.29	1.38	1.46	1.55	1.64	1.72	1.81	1.89
Gen. res.waste	58	62	67	71	76	80	84	89	93	98
ELRPt	11,912	12,821	13,730	14,639	15,548	16,457	17,366	18,275	19,184	20,093

Name	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	Sum
Total env. impact after	78,669,823	81,077,769	83,485,715	85,893,661	88,301,607	90,709,554	93,117,500	95,525,446	97,933,392	100,341,338	1,549,315,401
ETWRt	23,967,691	24,702,574	25,437,457	26,172,339	26,907,222	27,642,105	28,376,987	29,111,870	29,846,752	30,581,635	
ETWNRt	8,527,531	8,900,374	9,273,216	9,646,058	10,018,901	10,391,743	10,764,586	11,137,428	11,510,271	11,883,113	
ECRt	6059.96	6233.61	6407.25	6580.89	6754.54	6928.18	7101.83	7275.47	7449.11	7622.76	
Water	0.0076	0.0078	0.0081	0.0083	0.0085	0.0087	0.0089	0.0092	0.0094	0.0096	
Natural gas	1.02	1.05	1.08	1.11	1.14	1.17	1.20	1.23	1.26	1.29	
Electricity	6,059	6,233	6,406	6,580	6,753	6,927	7,101	7,274	7,448	7,621	
EERt	12.60	12.96	13.33	13.69	14.05	14.41	14.77	15.13	15.49	15.85	
Mercury vapor	12.59	12.95	13.31	13.67	14.03	14.39	14.75	15.11	15.47	15.83	
Mercury(water)	0.0161	0.0165	0.0170	0.0174	0.0179	0.0184	0.0188	0.0193	0.0197	0.0202	
Residue waste	0	0	0	0	0	0	0	0	0	0	
ETPRt	32,942,869	33,865,098	34,787,327	35,709,556	36,631,785	37,554,014	38,476,243	39,398,472	40,320,701	41,242,930	
ETRWt	13,189,182	13,565,427	13,941,672	14,317,917	14,694,161	15,070,406	15,446,651	15,822,896	16,199,141	16,575,385	
ECRWSt	379.28	390.15	401.02	411.89	422.75	433.62	444.49	455.36	466.23	477.09	
Cement	333	343	352	362	371	381	390	400	409	419	
Sodium sulfide	44	45	46	47	49	50	51	52	54	55	
Water	0	0	0	0	0	0	0	0	0	0	
Electricity	2.48	2.55	2.62	2.69	2.76	2.83	2.91	2.98	3.05	3.12	
EERWSt	2.55	2.62	2.70	2.77	2.84	2.91	2.99	3.06	3.13	3.21	
Mercury vapor	0	0	0	0	0	0	0	0	0	0	
Gen. res.waste	2.55	2.62	2.70	2.77	2.84	2.91	2.99	3.06	3.13	3.21	
ECSt	14,989	15,638	16,286	16,935	17,584	18,233	18,881	19,530	20,179	20,828	
Cement	13,117	13,684	14,252	14,820	15,388	15,955	16,523	17,091	17,658	18,226	
Sodium sulfide	1,774	1,851	1,928	2,004	2,081	2,158	2,235	2,311	2,388	2,465	
Water	0	0	0	0	0	0	0	0	0	0	
Electricity	98	102	107	111	115	119	124	128	132	136	
EESt	104.04	108.55	113.05	117.55	122.06	126.56	131.06	135.56	140.07	144.57	
Mercury vapor	1.98	2.06	2.15	2.24	2.32	2.41	2.49	2.58	2.66	2.75	
Gen. res.waste	102	106	111	115	120	124	129	133	137	142	
ELRPt	21,002	21,911	22,820	23,729	24,638	25,547	26,456	27,365	28,274	29,183	

All kinds of cost impact happened from optimum in decision.

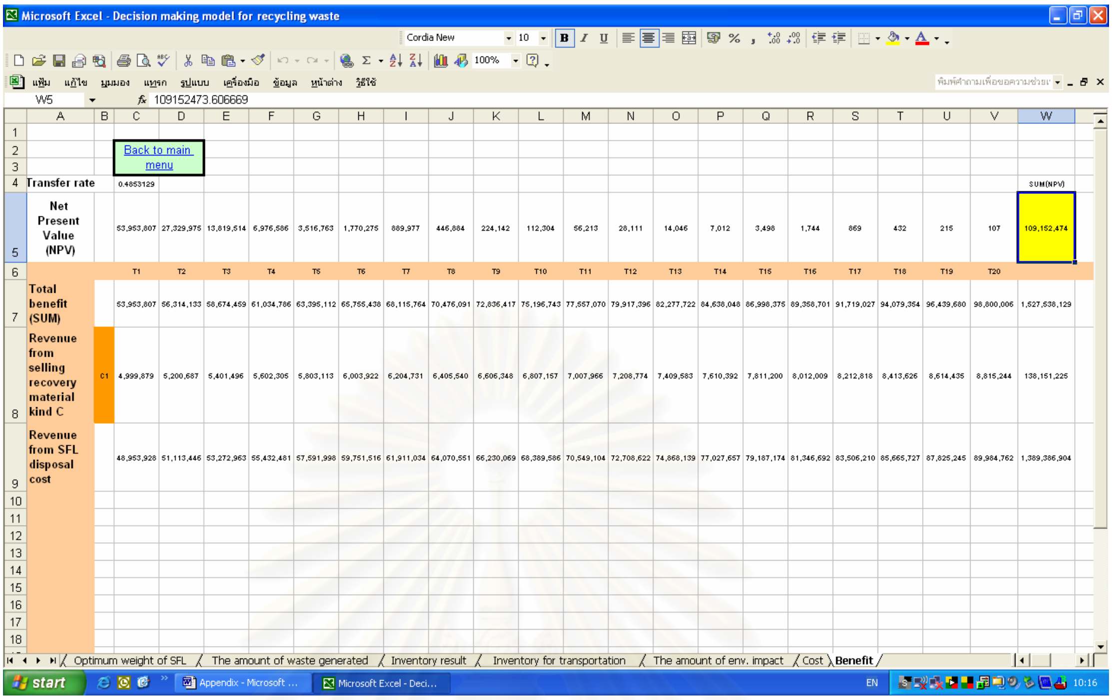


C2 Back to main menu

		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Transfer rate		0.4853									
Net Present Value (NPV)		71,385,201	15,940,854	6,121,170	3,544,917	1,779,271	998,720	446,834	223,592	111,782	61,750
Total cost		71,385,201	32,846,549	25,989,074	31,012,774	32,074,123	37,096,647	34,199,171	35,261,696	36,324,220	41,346,744
Total transportation cost (SUM)		1,276,316	1,340,182	1,405,225	1,471,443	1,535,310	1,600,352	1,665,395	1,730,437	1,795,480	1,860,522
Cost of transport waste to recycling process		929,696	969,579	1,010,638	1,052,873	1,092,756	1,133,815	1,174,874	1,215,933	1,256,992	1,298,051
Cost of transport waste to non-recycling process		268,133	288,964	309,796	330,627	351,458	372,289	393,121	413,952	434,783	455,614
Recycling process cost (SUM)		67,612,062	28,819,014	21,705,966	26,472,917	27,279,869	32,046,821	28,893,772	29,700,724	30,507,676	35,274,628
All consumed raw mat.&energy											
Water	K1	28,648	29,798	30,949	32,099	33,250	34,400	35,551	36,702	37,852	39,003
Natural gas	K2	6,017	6,259	6,501	6,742	6,984	7,226	7,467	7,709	7,951	8,192
Electricity	K3	117,097	121,800	126,503	131,206	135,909	140,612	145,315	150,018	154,721	159,424
Residue waste disposal cost		2,848,768	2,963,182	3,077,597	3,192,011	3,306,425	3,420,839	3,535,254	3,649,668	3,764,082	3,878,496
Labor cost		17,091,532	17,777,974	18,464,416	19,150,859	19,837,301	20,523,743	21,210,186	21,896,628	22,583,070	23,269,512
Maintenance and Land Rent cost		14,400,000	2,400,000	0	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	1,200,000	2,400,000
Investment Cost		33,120,000	5,520,000	0	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	2,760,000	5,520,000
Machine		22,320,000	3,720,000	0	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	1,860,000	3,720,000
Construction facilities		10,800,000	1,800,000	0	900,000	900,000	1,800,000	900,000	900,000	900,000	1,800,000
Non-recycling process cost (SUM)		2,496,823	2,687,353	2,877,883	3,068,414	3,258,944	3,449,474	3,640,004	3,830,534	4,021,065	4,211,595

	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	SUM(NPV)
Net Present Value (NPV)	27,868	13,898	6,926	3,778	1,717	854	462	211	105	52	100,669,963
Total cost	38,449,269	39,511,793	40,574,318	45,596,842	42,699,366	43,761,891	48,784,415	45,886,939	46,949,464	48,011,988	817,762,485
Total transportation cost (SUM)	1,925,565	1,990,607	2,055,649	2,120,692	2,185,734	2,250,777	2,315,819	2,380,862	2,445,904	2,510,947	37,863,218
Cost of transport waste to recycling process	1,339,110	1,380,169	1,421,228	1,462,287	1,503,346	1,544,405	1,585,464	1,626,523	1,667,582	1,708,641	26,373,964
Cost of transport waste to non-recycling process	476,446	497,277	518,108	538,939	559,771	580,602	601,433	622,264	643,096	663,927	9,320,601
Recycling process cost (SUM)	32,121,579	32,928,531	33,735,483	38,502,434	35,349,386	36,156,338	40,923,290	37,770,241	38,577,193	39,384,145	693,762,069
All consumed raw mat.&energy											
Water	40,153	41,304	42,454	43,605	44,755	45,906	47,057	48,207	49,358	50,508	791,558
Natural gas	8,434	8,676	8,917	9,159	9,401	9,642	9,884	10,126	10,367	10,609	166,263
Electricity	164,127	168,830	173,533	178,236	182,939	187,641	192,344	197,047	201,750	206,453	3,235,506
Residue waste disposal cost	3,992,911	4,107,325	4,221,739	4,336,153	4,450,568	4,564,982	4,679,396	4,793,810	4,908,225	5,022,639	78,714,070
Labor cost	23,955,955	24,642,397	25,328,839	26,015,282	26,701,724	27,388,166	28,074,608	28,761,051	29,447,493	30,133,935	472,254,672
Maintenance and Land Rent cost	1,200,000	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	2,400,000	1,200,000	1,200,000	1,200,000	42,000,000
Investment Cost	2,760,000	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	5,520,000	2,760,000	2,760,000	2,760,000	96,600,000
Machine	1,860,000	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	3,720,000	1,860,000	1,860,000	1,860,000	65,100,000
Construction facilities	900,000	900,000	900,000	1,800,000	900,000	900,000	1,800,000	900,000	900,000	900,000	31,500,000
Non-recycling process cost (SUM)	4,402,125	4,592,655	4,783,185	4,973,716	5,164,246	5,354,776	5,545,306	5,735,836	5,926,367	6,116,897	86,137,198

All kinds of Benefit happened from optimum in decision.



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	A	B	C	D	E	F	G	H	I	J	K	L
4	Transfer rate		0.4853129									
5	Net Present Value (NPV)		53,953,807	27,329,975	13,819,514	6,976,586	3,516,763	1,770,275	889,977	446,884	224,142	112,304
6			T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
7	Total benefit (SUM)		53,953,807	56,314,133	58,674,459	61,034,786	63,395,112	65,755,438	68,115,764	70,476,091	72,836,417	75,196,743
8	Revenue from selling recovery material kind C	C1	4,999,879	5,200,687	5,401,496	5,602,305	5,803,113	6,003,922	6,204,731	6,405,540	6,606,348	6,807,157
9	Revenue from SFL disposal cost		48,953,928	51,113,446	53,272,963	55,432,481	57,591,998	59,751,516	61,911,034	64,070,551	66,230,069	68,389,586

	A	M	N	O	P	Q	R	S	T	U	V	W
4	Transfer rate											SUM(NPV)
5	Net Present Value (NPV)	56,213	28,111	14,046	7,012	3,498	1,744	869	432	215	107	109,152,474
6		T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	
7	Total benefit (SUM)	77,557,070	79,917,396	82,277,722	84,638,048	86,998,375	89,358,701	91,719,027	94,079,354	96,439,680	98,800,006	1,527,538,129
8	Revenue from selling recovery material kind C	7,007,966	7,208,774	7,409,583	7,610,392	7,811,200	8,012,009	8,212,818	8,413,626	8,614,435	8,815,244	138,151,225
9	Revenue from SFL disposal cost	70,549,104	72,708,622	74,868,139	77,027,657	79,187,174	81,346,692	83,506,210	85,665,727	87,825,245	89,984,762	1,389,386,904

BIOGRAPHY

My name is Witoon Apisitpuvakul. I was born on 1 February 1976 at Bangkok, Thailand. I graduated Bachelor degree in Environmental Engineering from King Mongkut Institute of Technology Thonburi (KMUTT). After that, I graduated Master Degree in Environmental Engineering from Chulalongkorn University Bangkok, Thailand. For doctoral degree, the scholarship is granted from the National Center of Excellence for Environmental and Hazardous Waste Management (NCE-EHWM). Shell (Thailand) company limited (Shell Fund) is a scholarship for doctoral research. My working experience is started at environmental engineer at sun sung promotion company limited for one year and thereafter at prominent fluid control company limited as project coordinator position. After that, I applied to work with Bangkok Metropolitan Administration (BMA) in environmental and sanitary section. I had been selected as representative of BMA to training of environmental management program at Ulsan City, Republic of Korea.