MIDPOINT AND ENDPOINT LIFE CYCLE IMPACT ASSESSMENT AND ECO-EFFICIENCY OF A CHEMICAL DRUM PRODUCED FROM VIRGIN AND RECYCLED HDPE PELLETS

KANAPOT MAHASARO

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Thesis
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....
Mr. Kanapot Mahasaro
Candidate

....
Lect. Boonlue Kachenchart,
Ph.D. (Biological Sciences)
Major advisor

....
Lect. Ratchaphong Klinsrisuk,
Ph.D. (Urban Environmental Management)
Co-advisor

....
Asst.Prof. Charongpun Musikavong,
Ph.D. (Environmental Management)
Co-advisor

....
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochemistry)
Dean
Faculty of Graduate Studies
Mahidol University

....
Asst.Prof. Raywadee Roachanakanan,
Ph.D. (Ecology, Evolution and Systematics)
Program Director
Master of Science Program in Technology of Environmental Management
Faculty of Environment and Resource Studies
Mahidol University

Thesis
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was submitted to the Faculty of Graduate Studies, Mahidol University
for the degree of Master of Science
(Technology of Environmental Management)
on
October 10, 2016

....
Mr. Kanapot Mahasaro
Candidate

....
Asst.Prof. Phairat Usubharatana,
Ph.D. (Environmental System Engineering)
Chair

....
Lect. Boonlue Kachenchart,
Ph.D. (Biological Sciences)
Member

....
Lect. Ratchaphong Klinsrisuk,
Ph.D. (Urban Environmental Management)
Member

....
Asst.Prof. Charongpun Musikavong,
Ph.D. (Environmental Management)
Member

....
Prof. Patcharee Lertrit,
M.D., Ph.D. (Biochemistry)
Dean
Faculty of Graduate Studies
Mahidol University

....
Assoc.Prof. Kampanad Bhaktikul,
Ph.D. (Civil and Environmental Engineering)
Dean
Faculty of Environment and Resource Studies
Mahidol University

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Kanapot Mahasaro

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KANAPOT MAHASARO 5437651 ENTM/M

M.Sc. (TECHNOLOGY OF ENVIRONMENTAL MANAGEMENT)

THESIS ADVISORY COMMITTEE : BOONLUE KACHENCHART, Ph.D., RATCHAPONG KLINSRISUK, Ph.D., CHARONGPUN MUSIKAVONG, Ph.D.

ABSTRACT

The objectives of this research were to conduct midpoint to endpoint life cycle impact assessment and to evaluate eco-efficiency of two HDPE plastic drum production processes, which used virgin pellets (formula 1) and recycled pellets (formula 2) as the raw materials. The functional unit was a 20 liter plastic drum at 1.10 kg weight. The environmental accounting data was collected from a plastic drum factory in Phetchaburi province during June 2014 to July 2015. The assessment was carried out by ReCiPe2008 method.

The assessment revealed that the production process of formula 2 with mixed virgin and recycled plastic pellets had lower midpoint and endpoint impacts than the production process of formula 2 with only virgin plastic pellets. The total midpoint impact scores for formula 2 and 1 were 5.58E-03 and 6.28E-03, respectively. The highest impacts of formula 1 and 2 were on fossil depletion, which were 59.1% and 50.8% of the total midpoint impacts, respectively. The total endpoint impact score of formula 2 and 1 production process were 0.9855Pt and 1.1453Pt, respectively. The highest impacts of formula 1 and 2 were on damage of natural resources, which were 54.0% and 48.1%, respectively. The major environmental impact was occurred during the stages of raw material obtainment and drum recycle. The evaluation of eco-efficiency indicated that formula 2 production process (0.35 Kg/KgOil-eq) had higher values than formula 1 (0.25 Kg/KgOil-eq). The results showed that formula 2 plastic drum production process was appropriated for the production development by the manufacturer. The process could be applied for increasing the production efficiency and at the same time reducing the environmental impacts.

KEY WORDS: LIFE CYCLE IMPACT ASSESSMENT/ ECO-EFFICIENCY/ HIGH DENSITY POLYETHYLENE VIRGIN PELLETS/ PRIMARY RECYCLE PELLETS/ SECONDARY RECYCLE PELLETS

184 pages

การประเมินวัฏจักรชีวิตผลกระทบขั้นกลางถึงขั้นปลายและประสิทธิภาพเชิงนิเวศเศรษฐกิจของการผลิตถังบรรจุภัณฑ์เคมีจากเม็ดพลาสติก HDPE ใหม่และรีไซเคิล

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คณพศ มหาสาโร 5437651 ENTM/M

วท.ม. (เทคโนโลยีการบริหารสิ่งแวดล้อม)

คณะกรรมการที่ปรึกษาวิทยานิพนธ์: บุญลือ คะเชนทร์ชาติ, Ph.D., รัชพงษ์ กลิ่นศรีสุข, Ph.D., จรงค์พันธ์ มุสิกะวงศ์, Ph.D.

บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินผลกระทบสิ่งแวดล้อมขั้นกลางถึงขั้นปลายและประสิทธิภาพเชิงนิเวศเศรษฐกิจของกระบวนการผลิตถังพลาสติกโพลีเอทิลีนความหนาแน่นสูง 2 ชนิด ที่ใช้เม็ดพลาสติกใหม่ (สูตร 1) และเม็ดพลาสติกรีไซเคิลเป็นส่วนผสม (สูตร 2) กำหนดให้หน่วยการทำงานคือ ถังพลาสติกขนาด 20 ลิตร จำนวน 1 ใบ น้ำหนัก 1.10 กิโลกรัม ดำเนินการเก็บข้อมูลบัญชีสิ่งแวดล้อมจากโรงงานผลิตถังพลาสติกแห่งหนึ่งในจังหวัดเพชรบุรี ระหว่างเดือน มิถุนายน 2557 ถึงเดือน กรกฎาคม 2558 ทำการประเมินตามวิธีของ ReCiPe2008

ผลการประเมินพบว่ากระบวนการผลิตถังพลาสติกด้วยสูตร 2 ที่ใช้เม็ดพลาสติกบริสุทธิ์ผสมกับเม็ดพลาสติกรีไซเคิลส่งผลกระทบต่อสิ่งแวดล้อมขั้นกลาง และขั้นปลายน้อยกว่ากระบวนการผลิตด้วยสูตร 1 ที่ใช้เม็ดพลาสติกบริสุทธิ์เพียงอย่างเดียว โดยกระบวนการผลิตด้วยสูตร 2 และ 1 ผลกระทบขั้นกลางรวม มีค่า 5.58E-03 และ 6.28E-03 ตามลำดับ โดยผลกระทบสิ่งแวดล้อมที่เกิดจากกระบวนการผลิตด้วยสูตร 1 และ 2 มากที่สุดคือการลดลงของเชื้อเพลิงฟอสซิล คิดเป็นร้อยละ 59.1 และ 50.9 ของผลกระทบสิ่งแวดล้อมขั้นกลางทั้งหมด ส่วนผลกระทบสิ่งแวดล้อมขั้นปลายรวมโดยกระบวนการผลิตด้วยสูตร 2 และ 1 มีค่า 0.9855Pt และ 1.1453Pt ตามลำดับ ซึ่งกระบวนการผลิตด้วยสูตร 1 และ 2 ก่อให้เกิดความเสียหายทางสิ่งแวดล้อมด้านทรัพยากรธรรมชาติมากที่สุด คิดเป็นร้อยละ 54.0 และ 48.1 ของผลกระทบสิ่งแวดล้อมขั้นปลายทั้งหมด ซึ่งผลกระทบสิ่งแวดล้อมส่วนใหญ่เกิดจากขั้นตอนการได้มาซึ่งวัตถุดิบและการนำถังกลับมาใช้ใหม่ ผลการประเมินประสิทธิภาพเชิงนิเวศเศรษฐกิจพบว่ากระบวนการผลิตด้วยสูตร 2 (0.35 Kg/Kg.oil-eq) มีค่ามากกว่าสูตร 1 (0.25 Kg/Kg.oil-eq) ผลการศึกษาบ่งชี้ว่าการผลิตถังพลาสติกด้วยสูตร 2 มีความเหมาะสมที่จะนำไปใช้พัฒนากระบวนการผลิตเพื่อให้ผู้ประกอบการสามารถเพิ่มประสิทธิภาพการผลิตและลดผลกระทบต่อสิ่งแวดล้อมได้พร้อมกัน

184 หน้า

CONTENTS

	Page
ACKNOWLEDGEMENTS	**iii**
ABSTRACT (ENGLISH)	**iv**
ABSTRACT (THAI)	**v**
LIST OF TABLES	**ix**
LIST OF FIGURES	**xiii**
CHAPTER I INTRODUCTION	**1**
1.1 Background and significance of the problem	1
1.2 Objectives	2
1.3 Scope of study	2
1.4 Conceptual framework	4
1.5 Hypothesis	5
1.6 Expected outcome	5
1.7 Definitions	5
CHAPTER II LITERATURE REVIEW	**6**
2.1 Life cycle assessment (LCA)	6
2.1.1 Goal and scope definition	7
2.1.2 Life cycle inventory analysis	7
2.1.3 Life cycle impact assessment	8
2.1.4 Life cycle interpretation	18
2.2 Life cycle assessments of plastic drums	18
2.2.1 Scope of study for the life cycle assessments of plastic drums	19
2.2.2 Life cycle inventory of raw materials	20
2.2.3 Plastic drum production process	35

CONTENTS (cont.)

		Page
	2.2.4 Shipping	40
	2.2.5 Application procedure	42
	2.2.6 Product management procedure after use	42
2.3	Eco-efficiency assessment	43
	2.3.1 Eco-efficiency assessment	43
	2.3.2 Pollution prevention cost	52
2.4	Related research	53
CHAPTER III	**METHODOLOGY**	**63**
3.1	Study goal	63
	3.1.1 Study goal	63
	3.1.2 System boundary	63
	3.1.3 Functional unit	64
	3.1.4 Product system	64
3.2	Data collection	65
	3.2.1 Life cycle inventory of raw material	65
	3.2.2 Main production process	66
	3.2.3 Product distribution and transportation	68
	3.2.4 Usage	68
	3.2.5 After usage (Disposal)	68
3.3	Data analysis	68
	3.3.1 Life cycle assessment	68
	3.3.2 Sensitivity analysis	69
3.4	Life cycle interpretation	70
	3.4.1 Comparison of eco-efficiency of plastic drum production process	70
	3.4.2 Pollution prevention cost analysis	71
	3.4.3 Comparison study	71

CONTENTS (cont.)

		Page
	3.4.3 Comparison study	71
CHAPTER IV RESULTS AND DISCUSSION		**72**
4.1	Life cycle inventory of high-density polyethylene plastic drum	72
	4.1.1 Life cycle inventory of raw materials	72
	4.1.2 High-density polyethylene plastic drum production	78
4.2	Life cycle assessment of High-density polyethylene plastic	79
	4.2.1 Life cycle inventory of plastic drum production process	79
	4.2.2 Environmental impact assessment of polyethylene plastic drum production process	80
4.3	Sensitivity Analysis	88
4.4	Interpretation and suggestion for improvement	89
	4.4.1 Production cost of each plastic drum	89
	4.4.2 Pollution preventive cost	92
	4.4.3 Improvement and suggestion	93
	4.4.4 Result of Eco-Efficiency of HDPE plastic Drums	97
	4.4.5 Comparison Study	100
CHAPTER V CONCLUSIONS		**102**
5.1	Conclusions	102
5.2	Suggestions	103
REFERENCES		**105**
APPENDIX		**108**
BIOGRAPHY		**184**

LIST OF TABLES

Table		Pages
2.1	Impact categories at the midpoint level	10
2.2	Impact categories at the endpoint level	10
2.3	Normalization reference values at midpoint level	12
2.4	Normalization reference values at endpoint level	13
2.5	The proportion of the energy used of electricity production during 2540-2554.	16
2.6	The power consumption and waste emission of crude oil production	22
2.7	The power consumption and waste emission of Natural gas production	22
2.8	The power consumption and waste emission of crude oil production	23
2.9	The power consumption and waste emission of Natural gas production	23
2.10	GHG emissions from the production of crude oil and natural gas.	24
2.11	Energy consumption and waste emission of polyethylene production	25
2.12	Energy consumption and waste emission of HDPE pellet (Olefin) production type 1 (gate-to-resin)	26
2.13	Energy consumption and waste emission of HDPE pellet (Olefin) production type 2 (cradle-to-resin)	27
2.14	Energy consumption and the waste emission from the production of recycled plastic HDPE.	33
2.15	Normalized eco-profile of 1 kg of HDPE (recycling or manufacturing)	34
2.16	Maximum amount of metals in pigments and dyestuff	35
2.17	Production data of HDPE plastic drum by blow molding process	39
2.18	The GHG emissions in the manufacturing process of plastic bottles.	40

LIST OF TABLES (cont.)

Table		Pages
2.19	The GHG emissions from the transportation distance.	41
2.20	Energy consumption of virgin and recycle process	42
2.21	Performance and Environmental impact of products	47
2.22	Economic valuation of external costs with the kerbside scheme	51
2.23	Pollution prevention cost of midpoint level	52
2.24	Environmental impact comparison of HDPE waste between disposal and recycle	53
2.25	Global warming impact of Virgin and Recycle HDPE pellets	54
2.26	Impact assessment result for the HDPE bottle scenario with recycling in the UK as the waste management option (per functional unit)	55
2.27	Impact assessment result for the HDPE bottle scenario with recycling in the China as the waste management option (per functional unit)	56
2.28	Contribution of the difference compartments to the single score of the two system in each of the LCIA methods studied	57
2.29	Environmental impact assessment of HDPE virgin	58
2.30	Environmental impact assessment of HDPE recycle	58
2.31	Environmental impact assessment of HDPE and PET bottle production	59
2.32	Greenhouse gas emissions in different size of packaging	60
2.33	GHG Emission data of HDPE plastic bag production	60
2.34	Life cycle inventory for 1500 plastic bags and 1000 paper bags	61
2.35	Net benefit of recycling 1 tonnes of waste material	62
4.1	Life cycle inventory data of inline recycle pellets of crushing process	73
4.2	Life cycle inventory data for collection and transportation process	74

LIST OF TABLES (cont.)

Table		Pages
4.3	Life cycle inventory data of washing process	75
4.4	Life cycle inventory data of crushing process	76
4.5	Transportation data of raw material	78
4.6	Life cycle inventory data for production process of plastic drum	79
4.7	Life cycle inventory data for production of plastic drum 2 formulas	80
4.8	Environmental impact assessment of midpoint level	82
4.9	Environmental impact assessment of midpoint level with normalization	83
4.10	Environmental impact assessment of midpoint impact by process step	85
4.11	Environmental impact assessment of endpoint level w	87
4.12	Environmental impact assessment of endpoint level with single score	87
4.13	Sensitivity analysis of percentage of collection change	88
4.14	Sensitivity analysis of ratio secondary recycle pellets mixing change	88
4.15	Production cost of formula1	90
4.16	Production cost of Sorting process 1 ton of primary recycle pellets	91
4.17	Production cost of formula 2	91
4.18	Production cost of secondary recycle pellets	92
4.19	Pollution preventive cost of each plastic drum	93
4.20	Adjustment of plastic scrap proportion in production process	94
4.21	The traditional methods to collection of plastic drum	95
4.22	The new approach methods to collection of plastic drum	96
4.23	Database of plastic drum production formula 2 for improvement	97
4.24	Plastic drum production after improvement	99

LIST OF TABLES (cont.)

Table		Pages
4.25	Eco-efficiency comparison of plastic drum between before and after improvement	100
4.26	Comparison of GHG emission of plastic packaging	101

LIST OF FIGURES

Figure		Page
1.1	Conceptual framework	4
2.1	Stage of life cycle assessment	7
2.2	Material flow of life cycle assessment	8
2.3	Environmental impact assessment by ReCiPe 2008 method	9
2.4	The environmental impact of petrochemical resins and bio-plastics.	15
2.5	Material flow of LCA and CFP assessment	19
2.6	Product system boundary	20
2.7	LCI of HDPE virgin pellets (FAL, 2011)	21
2.8	The synthesis of poly ethylene.	25
2.9	The growing trend of plastic recycling in America.	28
2.10	Production process of HDPE recycle pellets	32
2.11	Energy consumption of plastic production (Ref)	36
2.12	Production process of blow molding (ref)	37
2.13	Flow chart of Blow molding production process (ref)	38
2.14	Eco-efficiency assessment of TOYOTA product (Ref)	48
2.15	Eco-efficiency assessment of TOSHIBA product (Ref)	48
3.1	System boundary of plastic drum production	64
3.2	System boundary of plastic drum production formula 1	66
3.3	System boundary of plastic drum production Formula 2	67
4.1	LCI of inline recycles pellets	73
4.2	LCI of outline recycled pellets	77
4.3	Environmental impact assessment of midpoint level normalization by ReCiPe 2008 method	84

LIST OF FIGURES (cont.)

Figure		Page
4.4	Environmental impact assessment of midpoint of production process by ReCiPe 2008 method	86
4.5	Environmental impact assessment of endpoint level of plastic drum	87
4.6	Influence of the ratio of HDPE virgin pellets and secondary recycle pellets	89
4.7	Eco-efficiency comparison of plastic drum between before and after improvement	100

CHAPTER I
INTRODUCTION

1.1 Background and significance of the problem

Currently, plastic plays an essential role in our life because it is used as material for producing tools, instruments and equipment. Plastic industry in Thailand grows rapidly because of its substantially connections to other industries. In 2013, it was found that plastic industry grew up to level 5-10 and the industry tended to be involved with plastic pellets. In Thailand, the packaging industry covered 49.7% entrepreneurs of all plastic industries (Thansettakij, 2013). These entrepreneurs included importers and exporters, of which were the exporting to Japan for 15% and importing from China for 21% (Thansettakij, 2013). For European countries and America, the proportion is quite low and many laws are regulated to control and limit plastic usage in each country. However, they emphasized on reuse and in 2012, it was found that the European Union recycled plastics up to 5.4 million Ton (Plastics Institution of Thailand, 2013).

Although, plastic recycle can reduce garbage and production cost, recycled plastic production process contains various minor procedures that may significantly affect the environment. Accordingly, it is necessary to evaluate the worthiness of plastic recycling caused by environmental impacts from the process of each raw material obtainment to the demolition of remains. Evaluating life cycle is one of instruments that is popularly used to determine environmental impacts of products or services along with the life cycle to improve production process and products so that the impacts on environment are essentially minimized. Furthermore, it includes using instruments to support decision on selecting processes, materials as well as working guidelines to ultimately reduce environmental impacts (Jaruek *et.al*., 2006).

Other than environmental impact evaluation to compare efficiency of production process of each product, another vital issue is to evaluate eco-efficiency which is comparing values of products and environmental impacts. Since recycling process comprises various minor procedures, it requires more power and resources than pure plastics; therefore, it may lead to higher production cost.

For Thailand, both pure plastics and recycled plastics are widely used in the production processes but the studies to evaluate eco-efficiency were still limited. Thus, the researcher was interested in evaluating the life cycle of 2 models of HDPE tanks, which were produced from virgin plastic pellets and virgin mixed with recycled plastic pellets. The virgin plastic pellets in this study were collected from the production process and recycled inline, thus they were considered as the primary recycled plastic pellets. The recycled plastic pellets were plastic wastes that recycled outline to produce the secondary recycled plastic pellets. This research was carried out by evaluating the environmental impacts in middle level for 18 terms and terminal level for 3 terms according to the evaluation approach of ReCiPe 2008 with SimaPro 8.0. Besides, production cost of each type was evaluated to determine the eco-efficiency of these three products as alternatives for entrepreneurs that produce plastics in Thailand.

1.2 Objectives

1) To evaluate and compare the midpoint and endpoint environmental life cycles impacts of 2 types of plastic drum produced from virgin plastic pellets and virgin mixed with recycled plastic pellets.

2) To measure the eco-efficiency of 2 types of plastic drum production processes including inline and outline recycled processes.

3) To study the alternatives in producing plastic drums and assess the sensitivity of each process to reduce the environmental impacts and become economically worthwhile.

1.3 Scope of study

1) Study the production process of 2 types of HDPE plastic drums made from virgin plastic pellets (inline recycle of primary recycled plastic pellets) and virgin

mixed with recycled plastic pellets (outline recycle of secondary recycled plastic pellets).

2) Specify the functional unit of the product, which was a 20 liter HDPE plastic drum with the approximate weight of 1.10 kilogram.

3) Inventory analysis of the input and output components of each production procedure. The process was cradle-to-gate type (business-to-business: B2B) type from a manufacturer, and the data were collected for one year to create a list throughout the life cycle.

4) Assess the midpoint and endpoint environmental impacts throughout the life cycle of the plastic drums by following the ReCiPe 2008 method.

5) Evaluate the eco-efficiency and sensitivity analysis of each production process when the production factors change, against the environmental impact.

1.4 Conceptual framework

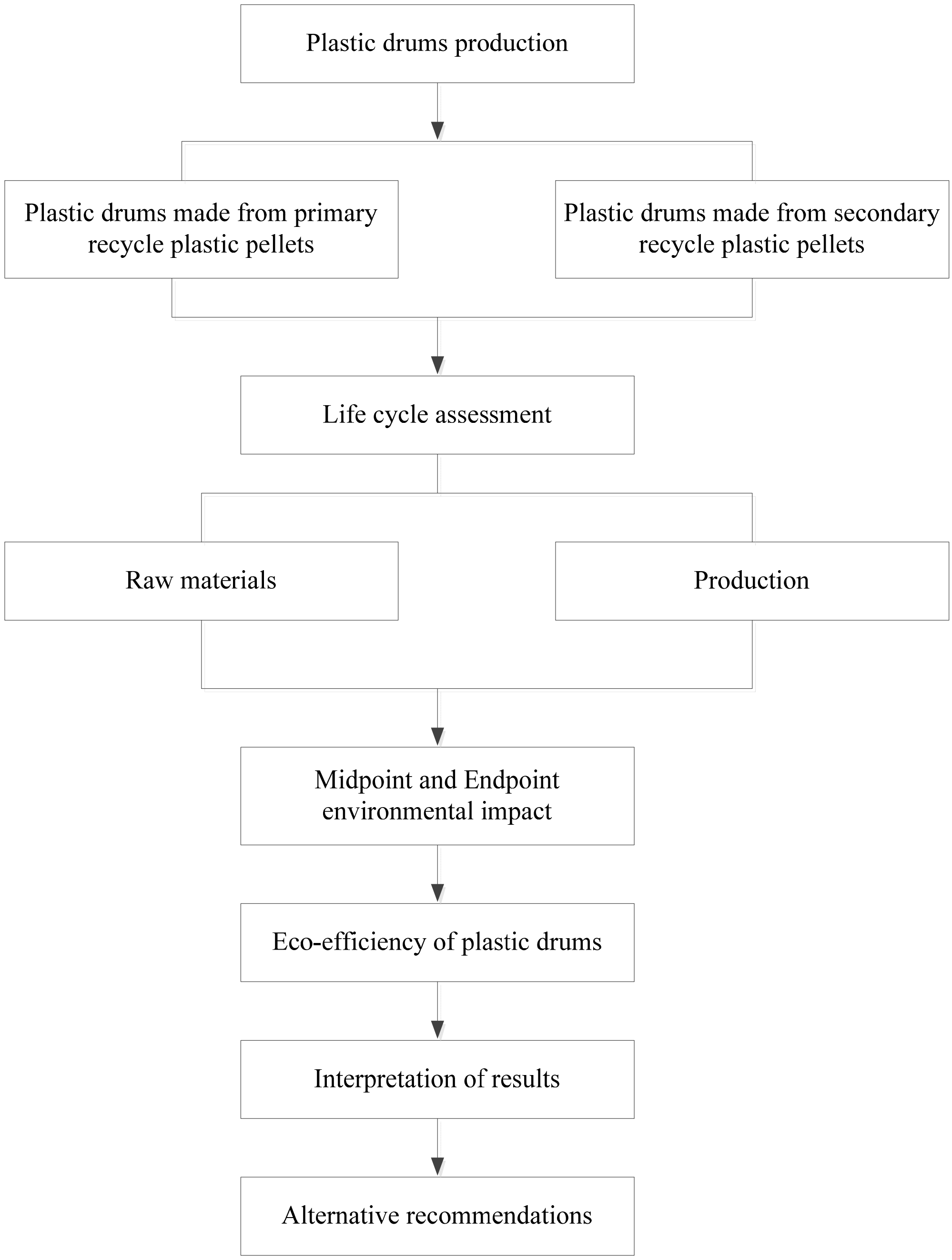

Figure 1.1 Conceptual framework

1.5 Hypothesis

1) Midpoint and endpoint environmental impacts for the production processes of both types of plastic drums were differ according to the production formula.

The eco-efficiency in the production of primary recycled plastic drums is lower than that of secondary recycle plastic drums.

1.6 Expected outcome

1) To gain fundamental information on resource and energy consumption, including waste discharge to the environment throughout the life cycle for both types of 20 liter HDPE plastic drums.

2) To gain knowledge on the environmental impacts from the productions of both types of HDPE plastic drums.

3) To produce environmental information to help companies to improve and develop the production process of each type of plastic.

4) To find an alternative for the manufactures to produce plastic drums that is suitable both in terms of production cost and environmental impact. It can also help create a nice image to the company in terms of environmental responsibility.

1.7 Definitions

1) Primary recycled plastic drums means drums that were made from recycled plastic pellets generated from the waste of virgin plastic pellets in the production process.

2) Secondary recycled plastic drums means drums that were made from recycled plastic pellets that were prepared by cleaning the used plastic waste and grinding them into pellets.

CHAPTER II
LITERATURE REVIEW

2.1 Life cycle assessment (LCA)

The society of environment toxicology and chemical: SETAC) defined LCA as “the procedure that assesses the environmental impacts by considering the production process and other related activities in the aspects of raw materials and energy. This assessment will be thoroughly throughout the life cycle of the product, such as the production process, packaging, sorting, maintenance, and recycling, as well as any other related activities. The principles of ecology, sanitation, and resource usage are held as the main principles for the assessment.”

As for international organization for standardization (ISO), defined LCA in the standard sequence ISO14040 as “the method to collect and evaluate the input and output substances, as well as the potential environmental impacts in the productive system throughout the life cycle.”

Life cycle assessment (LCA) is the procedure to analyze and evaluate the environmental impacts of the products throughout its life span; from the extraction or acquisition of raw material, production process, shipping and distribution, product usage, reuse and recycle, and the waste disposal after use. It could be said that the assessment would be from its birth to death (cradle to grave). Energy and resource consumption, as well as the amount of waste discharged to the environment, were specified in order to find a method to improve the product so that it has minimum impact on the environment. The 4 main scopes to conduct the assessment are 1) Goal and scope definition 2) Life cycle inventory analysis 3) Life cycle Impact analysis and 4) Life cycle interpretation (figure 2.1) (Thailand Environment Institute Foundation, 2004)

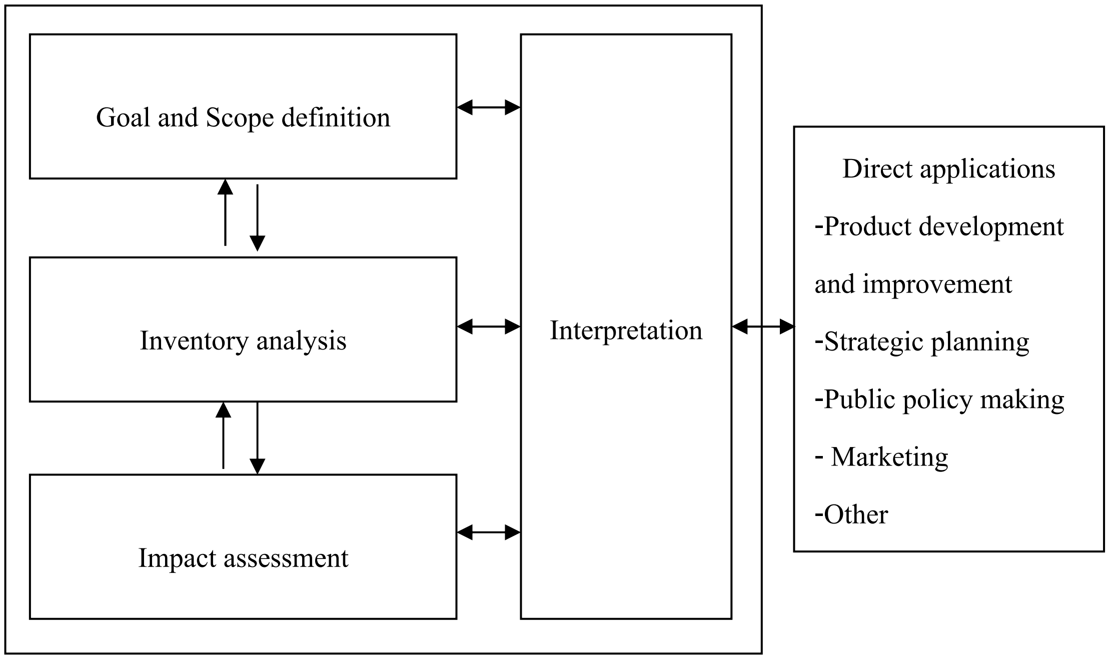

Figure 2.1 Stage of life cycle assessment
(Thailand Environment Institute Foundation [TEI], 2004)

2.1.1 Goal and scope definition

Defining the goal is an important step in the life cycle assessment of the product to clarify the objectives of the research and specify the system used in the study that meets the requirements. It directly influences the direction and thoroughness of the research. If the goal and scope are not defined well enough, then the input and output substances or the benefits to be gained from the improvement of the system would not be evaluated accurately and relevantly.

The procedures to define the goal and scope include defining the goal and scope, product functions, functional units, system boundary, and product system.

2.1.2 Life cycle inventory analysis

Inventory is the data that shows the quantity of the input, such as resource, energy, and public utilities; and the output, such as the main product, subordinate product, and water/air/soil pollution, together with the total environmental list of the chosen production process or product. The purpose of this inventory is to compile data related to the environment from the procedure defined in the scope definition step, along with generating a model of the product system, as shown in figure 2.2

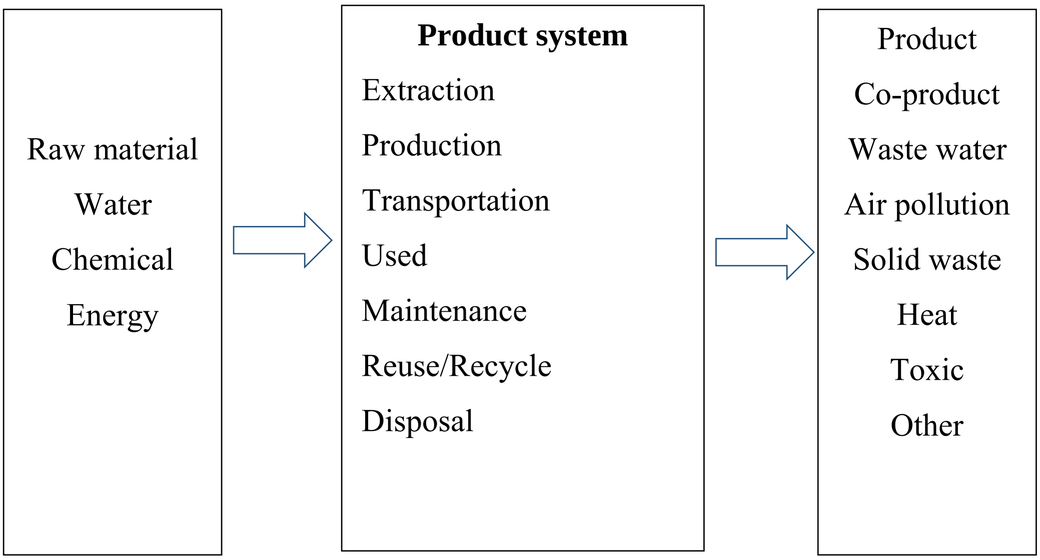

Figure 2.2 Material flow of life cycle assessment
(TEI, 2004)

2.1.3 Life cycle impact assessment

The aim of life cycle impact assessment is to evaluate the environmental impacts of the system of the product by using data on resource consumption and pollution discharge. Following the assessment principles stated in the 14042 standard, LCIA is divided into 2 steps as shown in figure 2-3: mandatory and optional.

2.1.3.1 Mandatory procedures

Mandatory procedures are obligatory procedures that must be compiled to assess the environmental impacts, in order to learn which aspects of the environment are affected by the resource and energy in the study system and in what quantity. It consists of 3 main steps, which are assorting the impact groups, classifying LCI data into the impact groups, and characterizing the data into environmental impact generation capability. The details of each step are stated below.

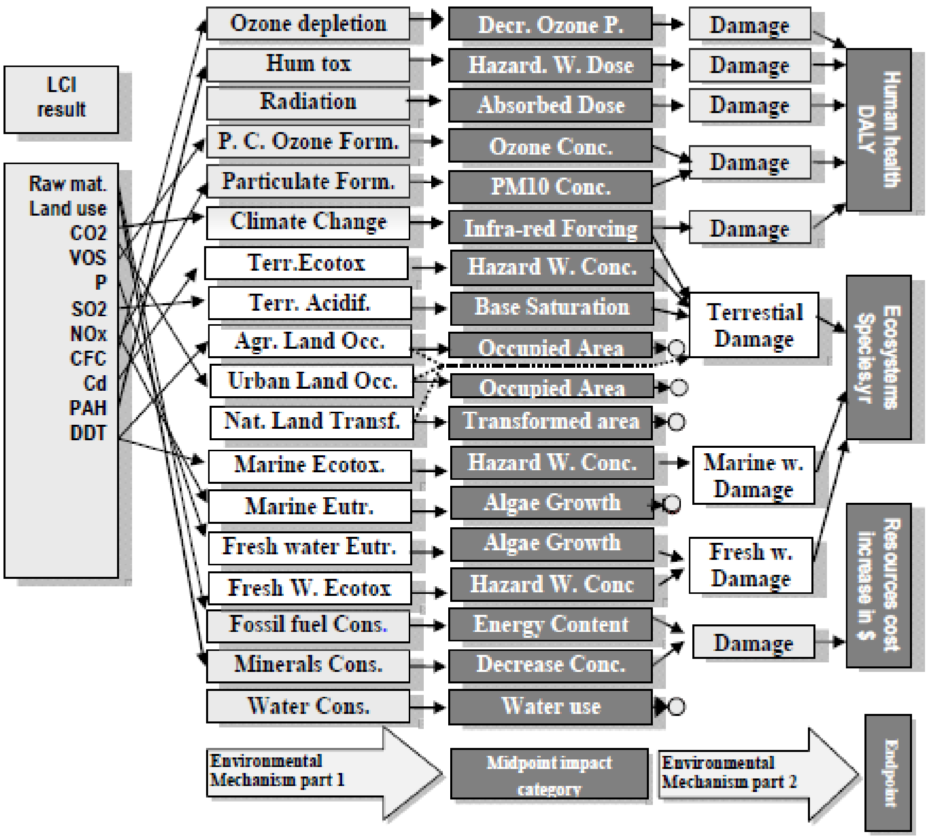

Figure 2.3 Environmental impact assessment by ReCiPe 2008 method (Goedkoop *et al*., 2009)

1) Assortment of impact groups

Assortment of impact groups is the procedure to assess the system of the product within the studied scope to see which sides of the environment it impacts and which procedures it occurs in. The data from the inventory analysis are analyzed and the environmental impacts of the input and output substances are categorized into groups. The environmental impacts of compiling LCIA can be separated into 2 categories: midpoint and endpoint, shown in table 2.1 and table 2.2, respectively.

Table 2.1 Impact categories at the midpoint level

Impact category	Abbreviation	Unit
Climate change	CC	Kg(CO_2 to air)
Ozone depletion	OD	Kg(CFC-11 to air)
Terrestrial acidification	TA	Kg(SO_2 to air)
Freshwater eutrophication	FE	Kg(P to freshwater)
Marine eutrophication	ME	Kg(N to freshwater)
Human toxicity	HT	Kg(14DCB to urban air)
Photochemical oxidant formation	POF	Kg(NMVOC to air)
Particulate matter formation	PMF	Kg (PM_{10} to air)
Terrestrial ecotoxicity	TET	Kg(14DCB to industry soil)
Freshwater ecotoxicity	FET	Kg(14DCB to freshwater)
Marine ecotoxicity	MET	Kg(14DCB to marine water)
Ionizing radiation	IR	Kg (U^{235} to air)
Agricultural land occupation	ALO	m^2 x yr (agricultural land)
Urban land occupation	ULO	m^2 x yr (urban land)
Natural land transformation	NLT	m^2(natural land)
Water depletion	WD	m^3(water)
Mineral resource depletion	MRP	Kg(Fe)
Fossil resource depletion	FD	Kg(oil)

Reference: Goedkoop *et al*. (2009)

Table 2.2 Impact categories at the endpoint level

Impact category	Abbreviation	Unit
Human Health	HH	DALY/p/yr
Ecosystem	ED	Species.yr/p/yr
Resources	RA	$/p/yr

Reference: Goedkoop *et al*. (2009)

2) LCI classification of LCI into impact groups

After selecting the impacts groups desired, the next procedure is to select the indicator for each impact group. Each impact group may have multiple impact indicators, so the endpoint impacts and indicators must be considered to be able to choose the most suitable one. This is due to the fact that endpoint impacts and indicators anticipate for improvement in the future. The criteria for consideration are the consistency with the objective of the LCA study, and consistency with the selected types of impact.

3) Characterization of data into environmental impact generation capability

Characterization of data into impact generation capability values is the conversion of the quantitative data of input and output substances within the same impact group to become environmental impact generation capability values. The standard indicators obtained from comparing the environmental impact generation capability value of the mentioned substance with the fundamental reference substance, are called the Equivalent or Characterization factors. It can be calculated from the model that explains the physics-chemistry mechanisms and pollution means in the environment, which are knowledge in the natural science field and accepted internationally. It is compiled by many organizations, such as IPCC, EIPD, Eco-indicator 95, Eco-indicator-99, ReCiPE, and so forth. Each organization compiles the above factor from different databases, thus, the user must choose the factor that is most suitable and closest to the point of study to achieve the most accurate results. The environmental impact value can be calculated from equation (1).

$$EP_j = \sum Q_i \times EF_{ij} \qquad (1)$$

Where EPj is the indicator result for impact category (j) (Kg substance equivalent)

Qi is the amount of substance (i) discharge into the environment. (Kg substance i)

EFij is the characterization factor (j) with impact category (i) (Kg substance equivalent/Kg substance j)

2.1.3.2 Optional procedures

Optional procedure to study is the procedure to evaluate the results of the resource consumption and environmental impact when they are in relation with activities in the society, by using the value obtained from the characterization of the environmental impact value step to evaluate. There are various methods to choose from, such as normalization, grouping, and weighting.

1) Normalization value of environmental impact

Normalization of environmental impact generation capability values means the comparison of the magnitude of the environmental impact of the studied product with the magnitude at various levels. The results would show the impact level of the product or activity on the worldwide, continent or national scale, shown in table 2.3 and 2.4. This environmental impact generation capability value has both a midpoint and endpoint impact value, and it is created on worldwide, international organizations, and national scales. Each country must create these values to compare each side of the impact value. However, if the data mentioned are not yet available, databases from other countries with similar climate may be used accordingly.

Table 2.3 Normalization reference values at midpoint level

Impact category	Unit	Normalization reference				
		Denmark[a]	Korea[a]	China[a]	World[b]	Europe[b]
Global warming	kg CO_2-eq/pe-yr	8700	8700	8700	6890	11200
Acidification	kg SO_2-eq/pe-yr	101	56	36	38.2	34.4
Eutrophication	kg NO_3^--eq/pe-yr	260	67	61	7.34	10.1

Reference: Harnpon (2009)[a] ; Goedkoop *et al*. (2008)[b]

Table 2.4 Normalization reference values at endpoint level

Impact category	Unit	Normalization reference(World)		
		Individualist	Hierarchist	Egalitarian
Ecosystems	species.yr/p/yr	8.00E-04	9.17E-04	2.48E-03
Human health	DALY/p/yr	1.50E-02	1.35E-02	2.39E-02
Resources	$/p/yr	9.85E+01	2.45E+02	2.45E+02

Reference: Goedkoop *et al*., (2008)

This procedure to normalize the environmental impact generation capability values allows for the overall comparison of the severity of the environmental impacts of the studied products, by using equation (2).

$$NP_{j(product)} = EP_j / (T \times ER_j) \quad (2)$$

Where NPj is normalized environment impact potential of (j) (person)

T is lifetime of product (year)

ERj is normalization reference of (j) according to the environmental impact of regular j any of the actions of a person/year (kg substance equivalent/person/year)

2) Grouping of environmental impact

Grouping of environmental impact is the formation of environmental impacts into various categories, such as impact on human health and sanitation, destruction of ecology quality, diminution of natural resource and energy source quantity. It can also be sorted on region levels, such as escalation of minerals; or on worldwide levels, such as the potential in causing global warming, to understand the overall magnitude of environmental impact in each category.

3) Weighting the significance of environmental impact

Weighting the significance of environmental impact means the comparison of the significance of each category of environmental impact, called as the

Weighting factor. The criterion used to specify the order of significance of the environmental impact can be either in quantitative or qualitative aspects, depending on the factors the researchers have chosen to consider. The factors include magnitude and intensity of the environmental impacts, specifically the ones to be improved; characterization of environmental damage into money value to be analyzed economically, and application of social principles, for instance. The calculation can be found in equation (3).

$$WP_j = WF_j \times NP_j \tag{3}$$

Where WPj is weighting environmental impact potential (j)
WFj is weighting factor (j)

4) Data quality analysis

Data quality analysis is the reliability verification of the environmental impact evaluation before it is applied further on. Factors used in the consideration of the data quality consist of suitability and consistency of the used data and desired data specified in the goal and scope of the study, by considering the source of the data, time of collection, accuracy of measurement and calculation methods, and suitability to be the substitute of the missing data. Examples of the techniques used to analyze the data quality include sensitivity analysis to classify data, allocation, and environmental impact calculation.

4.1) Sensitivity analysis

Sensitivity check is the evaluation procedure on the results of the study due to change in the parameters. It can be done by varying the hypothesis and data, then comparing the results obtained. The sensitivity value will be in the form of alteration percentage or absolute deviation of that result.

There are many factors for the source of the sensitivity value of the data in the plastic bucket production process; so if there are any changes from the previous studied process, the evaluation results may differ. The factors can be divided into two main sections as follows.

4.1.1) Sensitivity from production factors

(1) Raw material

Raw material used in the plastic bucket production process consists of 2 main materials: resins and resin coloring. The alteration of the type of raw material used in the production process may cause variation on the evaluation results of the environmental impacts, especially in the case of resins as there are many kinds to choose from. From resins produced from petrochemical processes and those produced from natural materials, to biological resins, each type would have varying application properties. Studies show that the environmental impact generation for biological plastic has the tendency to be lower than that of plastic produced from petrochemicals (as shown in figure 2.4).

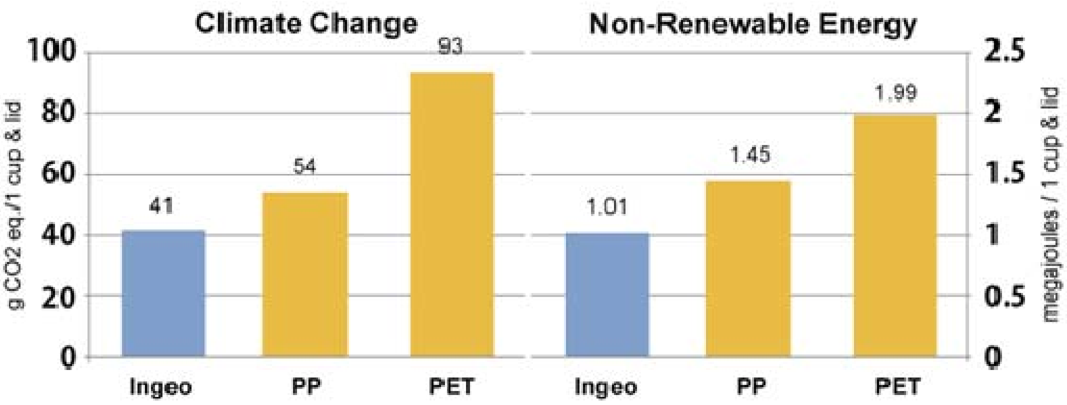

Figure 2.4 The environmental impact of petrochemical resins and bio-plastics. (Moore, 2013)

(2) Mixture ratio

In the case that there is a change in the formula or ratio of the resins mixture in the production process, the environmental impact value is also affected. This is especially significant for the plastic drums produced from secondary recycled resins which use a mixture of secondary recycled resins and pure resins. The ratio used would depend on the ratio specified by the production company, and the procedure to obtain each type of resin would differ in terms of both resource consumption and pollution discharge. Thus, if there is an alteration in the production formula, it may cause the environmental impact value to change as well.

(3) Energy consumption in the production process

The main energy used in the production process is electricity. At present, there are many types of energy used to produce electricity in Thailand; such as hydropower, natural gas, fuel oil, diesel fuel, lignite, coal, or even the importation of electricity from abroad (as shown in table 2.5). The essential energy used to produce electricity is mainly natural gas, which the consumption was as high as 55.7% in 2011. In the case that there is a change in the type of energy used to produce electricity, it would cause for the alteration in the evaluation of the environmental impacts since the acquisition of each type of energy differs from one another.

Table 2.5 The proportion of the energy used of electricity production during 2540-2554.

Fuel type	Ratio of electricity (%)					
	2540	2541	2542	2544	2549	2554
Hydropower	7.6	5.6	4.2	3.8	3.8	3
Natural gas	46.2	51.6	61.4	73.8	66.7	55.7
Fuel oil	20.6	20.4	16.6	3.9	3	5.1
Diesel	3.7	0.9	0.5	-	-	-
Lignite	20.3	18.9	13.3	13	11.8	8.4
Coal(import)	0.8	0.8	1.5	2.7	12.7	18.8
Electricity(import)	0.8	1.8	2.5	2.8	2	9
Total	100	100	100	100	100	100

Reference: Energy Policy and Planning Office [Eppo]. (1999)

(4) Energy consumption in the shipping process

There are many types of energy used for transport vehicles, obtained from both nature and from petrochemicals. Each type of energy has its own way of acquisition and own level of waste discharge to the environment. Examples of the types of energy used include petrol, natural gas, liquefied petroleum gas (LPG), and biodiesel. If there is any change in the aforementioned energy, it would affect the environmental impact value as well.

(5) Shipping distance

The difference in shipping distance for each scope of study may cause for the variation in the evaluation of environmental impact values. This includes the shipping distance of the resins to the packaging production factory, and the shipping from gathering the contaminated drums to be cleaned and grinded to become recycled resins, for instance. Shipping distance is in direct proportion with the amount of greenhouse gas discharged, as longer distance would naturally cause for higher amount of greenhouse gas discharge. The study of the life cycles of two plastic bottle sizes in Europe and Northern America revealed that the carbon discharge value from just the production process and distributional shipping process equal to more than half of the carbon discharge of the entire process. The value was found to be 77.4% in Europe, and 68.3% in Northern America. (Beverage Industry Environmental Round table, 2012)

4.1.2) Sensitivity from the study methods

(1) Study methods

There are many format to evaluate the life cycle of the product; for instance, Eco-indicator 95, Eco-indicator 99, ReCiPe 2008, EPS 2000, EDIP 97 and LIME. Each format gives different significance on each issue, depending on the surroundings and other evaluation factors, such as the characterization factor, normalization factor, weighting factor and single score value. Thus, choosing different evaluation methods may cause for difference in evaluation results.

(2) Allocation methods

There are many types for the allocation of the input and output substances in the system, in terms of both resource and energy consumption, such as allocation by weight, economical allocation, and technical allocation. Each type of allocation would change the factors in the production process, which may change the evaluation results as well.

2.1.4 Life cycle interpretation

The procedure to interpret LCA results is to combine the results obtained from the data inventory and from the impact evaluation to achieve conclusions and suggestions that follow the goal and scope of the study as defined. The interpretation may be done back and forth repeatedly to examine the data, and the scope of research may have to be changed to be consistent with reality or quality of the data gathered following the specified goal. Interpretation of results must also consider the sensitivity and uncertainty of the analysis.

2.2 Life cycle assessments of plastic drums

The Plastics Institute of Thailand specified that in 2012 the situation of resins usage in Thailand was still expanding continuously, up to 5-10%, due to the support from the automotive industry, in which the production for the entire year was at 2.2-2.4 million vehicles. The expansion was also due to the first-car policy from the government and the increase of packaging usage rate as a result of the recovering from the big flood in 2011 where those affected had to buy additional electronic appliances and utilities, which resulted in the expansion of the plastic industry.

In 2012 the total consumption of resins was approximately 4 million tons, and another 4 million tons was exported to Asia, USA, and Europe, which the export value of resins and plastic products accounts to approximately 400 billion baht per year. At present there are 3,000 members in the plastic industry, and up to 50% of the total amount of resins is used to produce packaging products. (The Federation of Thai Industries, 2011)

It can be seen that the plastic industry in Thailand is growing continuously, especially the plastic packaging production industry that can be used in various business groups. However, the entrepreneurs in the plastic industry in the future may have to adapt considerably to support the approach into the ASEAN Economic Community (AEC). This may cause both positive and negative effects, such as the import cost of raw materials may have the tendency to decrease, but on the other hand, the amount of competitors to snatch the market share may increase.

Thus, plastic industry entrepreneurs must adapt to support the aforementioned problems and to have the capability to compete in the market. There are many forms of adaptation for the plastic packaging industry, such as changing the design to be more convenient to use, designing new products that reduce the production cost, or designing new products that reduce the environmental impact.

At present, the designing of packaging that reduces environmental impact is receiving approval extensively. The significant tools used in the environmental impact assessment are the life cycle assessment and the GHG emission assessment of the product, which is the evaluation of the greenhouse gas emission in the form of equivalent carbon dioxide (equivalent kg CO_2) from the energy and resource consumption; as well as the pollution discharge of the product. The emission would be calculated from the acquisition of the raw materials, production process, and waste disposal, as seen in figure 2.5

2.2.1 Scope of study for the life cycle assessments of plastic drums

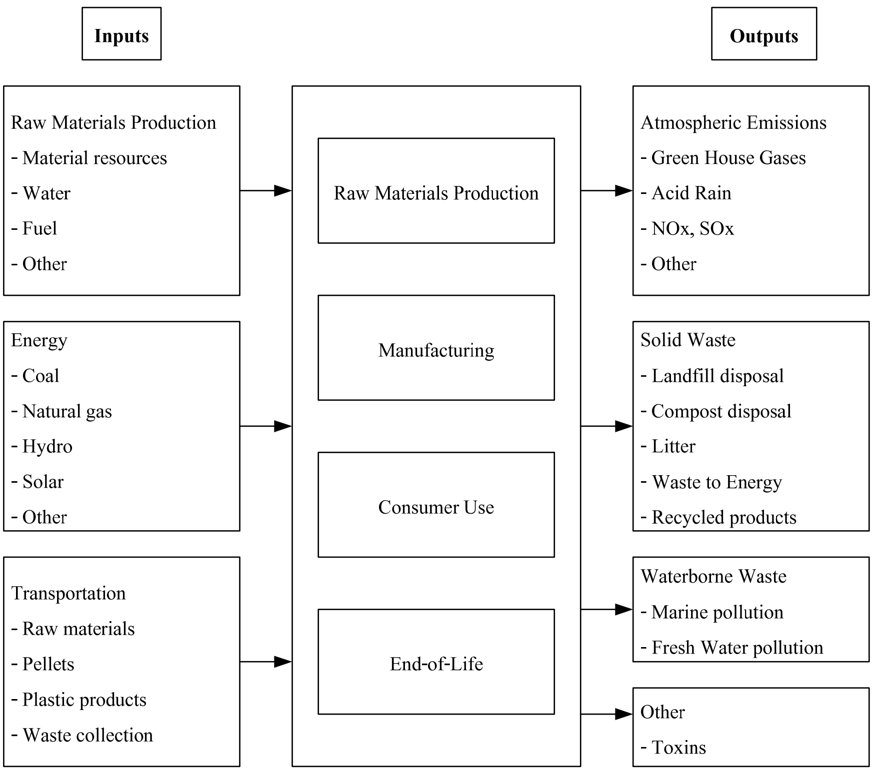

Figure 2.5 Material flow of LCA and CFP assessment (Lehman *et al*., 2005)

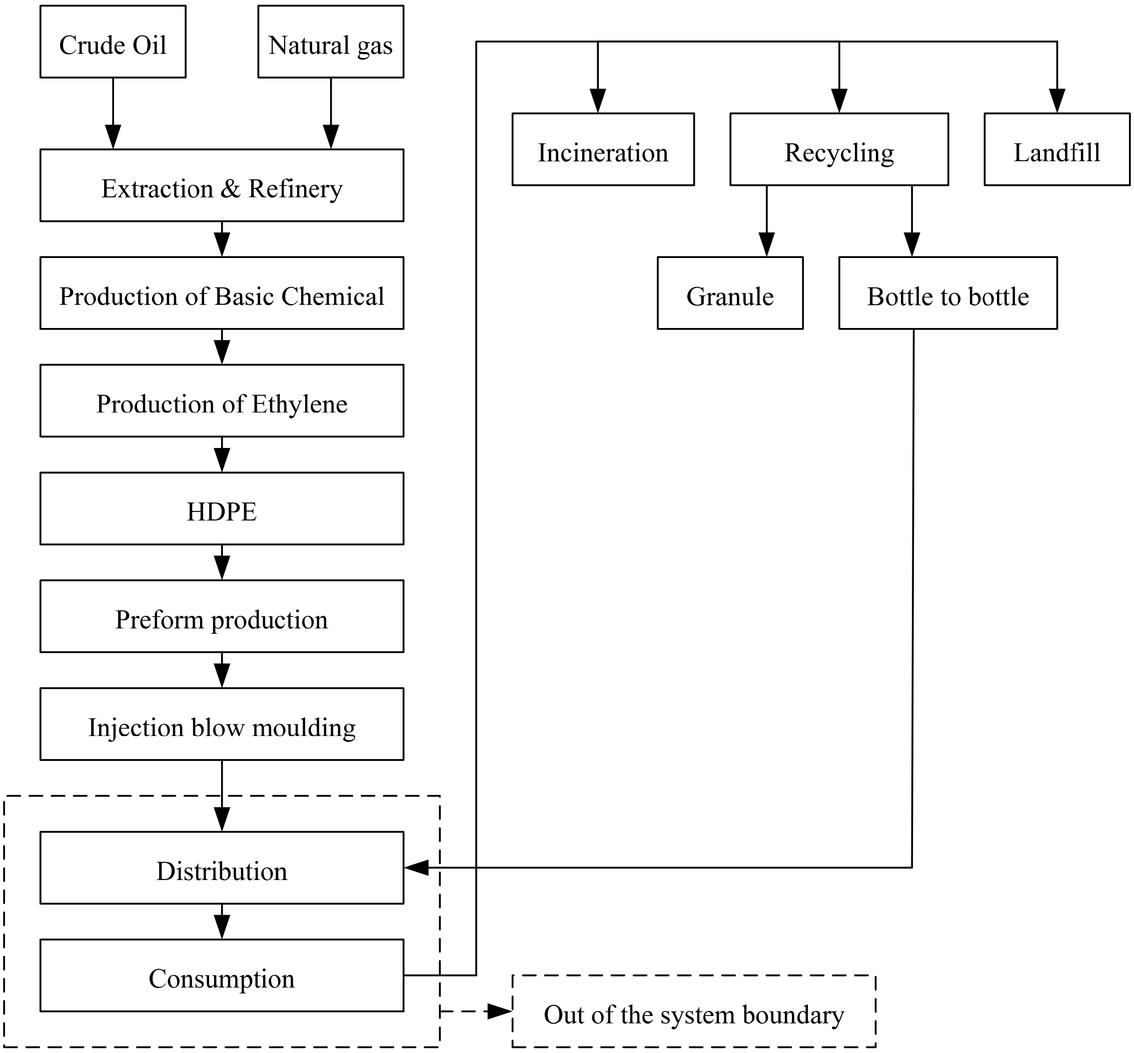

Figure 2.6 Product system boundary
(Lehman *et al*., 2005)

2.2.2 Life cycle inventory of raw materials

2.2.2.1 Production process of pure resins

1) production of crude oil and natural gas

Resins are an end product from two main initial substances, which are crude oil and natural gas. Each initial substance differs in methods of acquisition, in terms of both energy consumption and waste discharge into the environment. Thus, the life cycle and GHG emission assessments must cover from the acquisition of the raw materials to the end of the process. The procedure to obtain the initial substances to produce HDPE resins consist of these following main steps:

- Crude oil production
- Distillation, desalting and hydrotreating
- Natural gas acquisition
- Natural gas processing
- Olefin/Ethylene production
- HDPE resin production

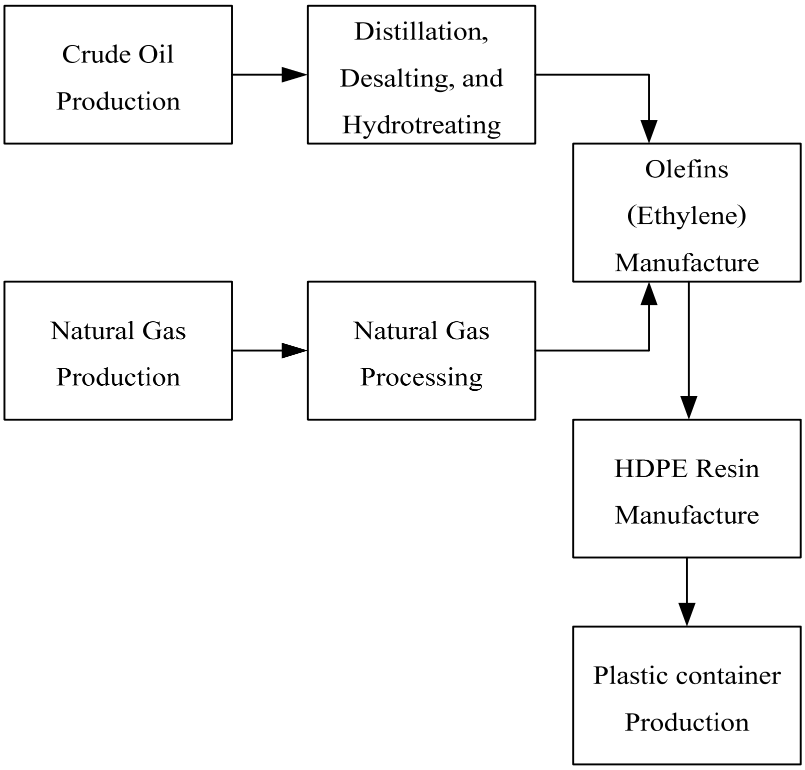

Figure 2.7 LCI of HDPE virgin pellets
(Franklin associates [FAL], 2011)

Crude oil is petroleum in liquid state in nature, mostly found to be black or brown. It is a mixture of different types of hydrocarbons, and in some cases there may be other substances combined as well, such as sulfur (S), nitrogen (N), and oxygen (O). Due to this fact, crude oil freshly extracted cannot be applied directly, but rather has to be separated into different groups of hydrocarbons before it can be applied following the uses of each type of substance. This method to separate the substances mixed in crude oil is called as the crude oil distillation process.

The production process of crude oil and natural gas starts from the procedure of obtaining the main raw materials, which is the procedure to excavate crude oil and natural gas. This procedure requires different types and quantity of energy and resource, such as fuel consumption for the excavation process and shipping process for each procedure. From studies, it is found that in the excavation of 1 ton of crude oil, the total energy consumption is 3.14 GJ and pollution discharge is 41.34 kg (as shown in table 2.6). On the other hand, in the excavation of 1 ton of natural gas, the total energy consumption is 1.93 GJ and pollution discharge is 55.35 kg (as shown in table 2.7).

Table 2.6 The power consumption and waste emission of crude oil production

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Petroleum	1,035	kg	Crude oil	1,000	kg
Energy for production	1.93	GJ	Air pollution	6.38	kg
Energy for transportation	1.21	GJ	Solid waste(landfill)	26.1	kg
			Waste water*	8.86	kg

Reference: FAL (2011)

Table 2.7 The power consumption and waste emission of Natural gas production

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Natural Gas	1,038	kg	Natural Gas	1,000	kg
Energy for production	1.93	GJ	Air pollution	20.4	kg
			Solid waste(landfill)	26.1	kg
			Waste water*	8.85	kg

Reference: FAL (2011)

After the excavation process, they will enter their respective production processes, in which the production process of crude oil consists of 3 main steps: distillation, desalting, and hydrotreating. The production process for both initial substances will differ in raw material and energy consumption, as well as pollution discharge, depending on each production procedure. In the production of 1 ton of oil, the total energy consumption is 3.63 GJ and pollution discharge is 8.02 kg (as shown in table 2.8). As for the production of 1 ton of natural gas, the total energy consumption is 2.61 GJ and pollution discharge is 58.24 kg (as shown in table 2.9). (FAL, 2011)

Table 2.8 The power consumption and waste emission of crude oil production

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Petroleum	1,018	kg	Crude oil	1,000	kg
Energy for production	3.41	GJ	Air pollution	2.126	kg
Energy for transportation	0.22	GJ	Solid waste(landfill)	5.6	kg
			Waste water*	0.292	kg

Reference: FAL (2011)

Table 2.9 The power consumption and waste emission of Natural gas production

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Natural Gas	1,005	kg	Natural Gas	1,000	kg
Energy for production	1.69	GJ	Air pollution	58.24	kg
Energy for transportation	0.92	GJ	Solid waste*	-	kg
			Waste water*	-	kg

Reference: FAL (2011)

Each country has different energy and resource consumption depending on various factors of that country. The difference in production process causes different carbon dioxide discharge quantities, which is one factor used in the GHG emission of the product. In the case that the oil is imported from overseas, if it is imported from a country that emits a high amount of carbon dioxide during the production process, the product would have a high carbon discharge value due to the raw material as well. The carbon discharge value from the crude oil production process for each country, from the excavation procedure until the product is obtained, is listed in table 2.10.

Table 2.10 GHG emissions from the production of crude oil and natural gas.

Field and Country	Production Volume (KBPD)	Overall Wellhead-to-Refinery emission (g CO_2/MJ)
Cantarell, Mexico	772	15.2
Mad Dog, USA	65	6.2
Steepbank, Canada	400	26.6
Hibernia, Canada	139	7.3
Kupal, Iran	55	30.5
Ghawar, Saudi Arabia	5319	7.9
Dacion, Venezuala	42	22.0
Bu Attifel, Libya	340	6.9
Samotlor, Russia	600	11.8
Duri, Indonesia	233	14.3
Forties, U.K.	63	8.0
Gullfaks, Norway	79	6.2

Reference: International Council on Clean Transportation [ICCT] (2010)

2) Production of resins from polyethylene

Production process of plastic begins by taking small hydrocarbon compounds obtained from the crude oil distillation process to react with each other until a long chain is achieved, called as polymer. Each type of polymer is synthesized from different initial raw materials, causing polymers to have various properties. These synthesized polymers will be formed into resins and produced further into many other products.

The production of polyethylene (PE) resins begins with the addition of a suitable catalyst into ethylene gas confined in a reaction chamber. The reaction will cause many small molecules to connect with each other and form a very long molecule, called as polyethylene, which has the properties suited to be formed into many products such as bottles, bags and toys.

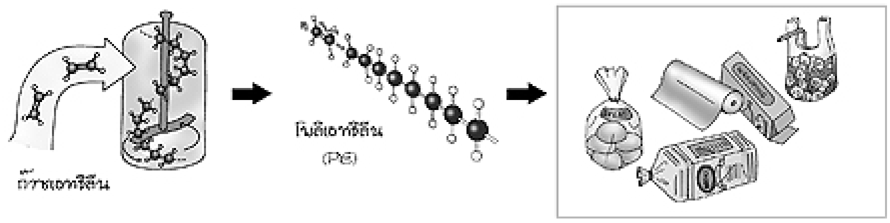

Figure 2.8 The synthesis of poly ethylene.
(National metal and material technology center [MTECH], 2013)

From studies it is found that in the production of 1 ton of polyethylene, the total energy consumption is 17.73 GJ and pollution discharge is 653.22 kg. The pollution discharge is mostly due to the air pollution caused from the combustion process, which accounts to 99.36% of the total pollution amount (as shown in table 2.11).

Table 2.11 Energy consumption and waste emission of polyethylene production

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Crude oil	186	kg	Ethylene	1,000	kg
Natural gas	830	kg	Air pollution(production)	0.221	kg
Water	1,627	liter	Air pollution(Combustion)	649.06	kg
Energy for production	17.7	GJ	Solid waste*	3.92	kg
Energy for transportation	0.031	GJ	Waste water**	0.015	kg

Reference: FAL (2011)

As for the procedure to assess the energy and resource consumption, as well as pollution discharge of the HDPE resins production process, it can be assessed in 2 forms. The first form is to evaluate the energy and resource consumption and pollution discharge values from the acquisition of polyethylene until the production into resins, called as the gate-to-resin assessment. While for the second form, it will evaluate the energy and resource consumption and pollution discharge values from the acquisition of the initial raw materials of the procedure, which is the acquisition of crude oil and natural gas, called as the cradle-to-resin assessment.

Both assessment methods have different energy and resource consumption and pollution discharge values. By producing 1 ton of HDPE resins with the Gate-to-Resin model, the total energy consumption is 5.50 GJ and total pollution discharge is 1.43 kg (as shown in table 2.12). On the other hand, by producing with the Cradle-to-Resin model, the total energy consumption is 77.9 GJ and pollution discharge is 112.96 kg (as shown in table 2.13).

Table 2.12 Energy consumption and waste emission of HDPE pellet (Olefin) production type 1 (gate-to-resin)

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Olefin	990	kg	HDPE pellets	1,000	kg
Water	1,494	liter	Air pollution	0.704	kg
Energy for production	5.50	GJ	Solid waste*	0.624	kg
			Waste water**	0.103	kg

Reference: FAL (2011)

Table 2.13 Energy consumption and waste emission of HDPE pellet (Olefin) production type 2 (cradle-to-resin)

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Crude oil	188	kg	HDPE pellets	1,000	kg
Natural Gas	827	kg	Air pollution	66.56	kg
Energy for extraction	49.4	GJ	Solid waste*	35.97	kg
Energy for production	27.3	GJ	Waste water**	10.43	kg
Energy for transportation	1.2	GJ			

Reference: FAL (2011)

2.2.2.2 Production process of recycled resins

1) Situation of recycled resins

At present, the tendency around the world to use recycled plastic is increasing continuously, including in the United States. Studies from Moore Recycling Associates Inc, as presented in The American Chemistry Council (ACC), found that USA has an increasing rate of recycling plastic, accounting for 72% from 2009, and increasing up to 154% from 2007, as seen in figure 2.8. Up to 31% of HDPE was recycled in 2011, second only to PP, which the recycle rate was as high as 39%. (Moore, 2013)

In addition, it can be seen that countries in Europe also give importance to recycling plastic as well. The European Plastic Recyclers (EuPR) have confirmed the success in the continuous growth of plastic recycling in Europe in the 2013 Annual Meeting. The plastic packaging recycle rate in Europe in 2012 was as high as 34.7%, and from recent statistics, every country in the Malta region has a 22.5% higher recycle rate than the minimum rate for the European Union. From the report of UK's Recoup and the European Association of Plastics Recycling & Recovery Organizations (Epro), specified that in 2012 the European Union was able to recycle up to 5.4 million tons of plastic, which was 33.6% higher than 2011. (Plastic Institute of Thailand, 2013)

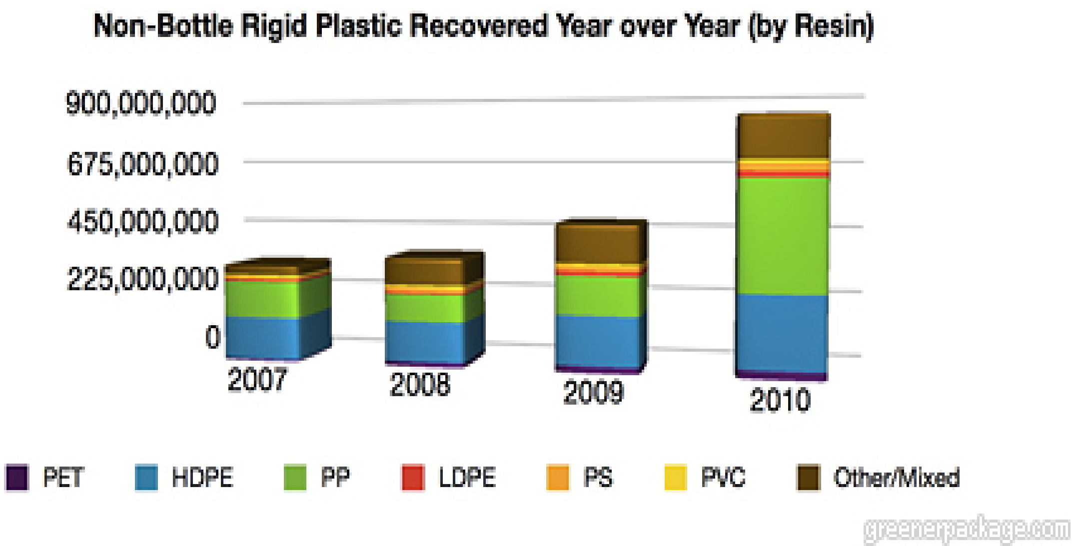

Figure 2.9 The growing trend of plastic recycling in America.
(Moore, 2013)

The cause for the continuous increase in the tendency to use recycled plastic each year is due to several factors, including the decrease in production cost and decrease in environmental impact. From the studies of 3 air cooling system manufacturers for automobiles, which are Rhodia, Valeo and PSA Peugot Citroen, the environmental impact from the usage of standard grade and recycled Technic Polyamide (PA) was compared. Results showed that by using recycled Technic Polyamide, it can reduce up to 9-28% of the environmental impact compared to using the standard grade. (Plastic Institute of Thailand, 2013)

From the recent study on "Final Report – Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer Containers and Packaging" compiled by Franklin Associates, confirms that by using recycled plastic, especially PET and HDPE, it can help save energy and reduce greenhouse gas emission tremendously. The study was constructed by using the Life Cycle Inventory (LCI)* method, to find the amount of energy, waste, and excess materials discharged from the production process required to gather the recycled PET resins and used HDPE products. It also includes for the procedures to classify raw materials, and the recycling process to produce clean recycled resins.

The results of the study by using LCI method and data from the Environmental Protection Agency (EPA) of USA, shows that the required amount of energy to produce recycled resins is lower than the amount required to produce pure PET and HDPE resins by 71 million Btu. In addition, it can reduce greenhouse gas emission up to 2.1 tons of equivalent carbon dioxide. The aforementioned study gained support from many organizations in the United States, which are the American Chemistry Council (ACC), Association of Postconsumer Plastic Recyclers (APR), National Association for PET Container Resources (NAPCOR), ad PET Resin Association (PETRA).

As for Thailand, there is also a continuous growth for the tendency to recycle plastic. Moreover, it can be seen that amount of entrepreneurs related to recycling has the tendency to increase as well. There are 208 entrepreneurs related to recycling, or 6.63%, from a total of 3,136 companies that manage a business related to plastic. This is lower than the amount of entrepreneurs related to resin production, which is as high as 2,338 companies or 74.55% of the total amount.

2) Types of recycled plastic

At present, reuse or recycling of plastic has been gaining a lot of attention, since apart from being able to reduce the amount of plastic waste; it is also a way to use the resources efficiently and effectively. Plastic recycling can be divided into 4 main categories: primary recycling, secondary recycling, tertiary recycling, and quaternary recycling.

2.1) Primary recycling takes plastic bottles or scraps that are of the same type with no contamination, created in the production or forming process, to be reused within the factory. It can be either reused entirely or mixed with new resins at various ratios.

2.2) Secondary recycling or reforming process is the procedure to clean, grind, melt, and reform used plastics into another plastic product. This secondary recycling category can also be divided into many techniques:

2.2.1) Mechanical recycling is the easiest and most used technique nowadays. Used plastic is collected and separated according to the type and color, then cleaned before being grinded into small parts. After that it will be melted into second grade resins or recycled resins to be reused as the raw material in the production process of a new product or mixed with pure resins to obtain the desired properties before entering the forming process. The quality of these recycled resins will determine the applications and required mixture ratios. The problem in the plastic recycling process is that every time it passes the recycling process, the quality of the plastic will decrease due to the breaks in the molecular chains. Thus it would not be able to be utilized to its maximum potential, and the price will reduce until sometimes it is not worthwhile to invest. One important reason is due to contamination of dirt, small labels, or bits of glue that would cause for a darker color or decrease in opacity for the recycled resins. Furthermore, the moistness in the plastics or the heat used in the melting process are also important factors that cause the degradation or separation of the molecular chains of the polymer, causing the recycled resins to become yellow and reduce the mechanical properties.

2.2.2) Chemical modification: As recycled resins have limitations in the properties, formation, and application aspects; thus, chemical modification will reduce the aforementioned limitations or create recycled resins to have similar characteristics as pure ones. This modification can be applied for either single-type plastics or mixtures. For single-type plastics, chemicals will be added or processed through radiation method; whereas for plastic mixtures, chemicals will be added to stabilize the blends of immiscible polymers. These chemicals are commonly known as compatibilizers.

2.2.3) Co-extrusion and co-injection molding is another technique for secondary recycling that is suitable for packaging products that have contact with food. The structure for plastic products produced from this procedure will be in layers, like sandwiches. The outer layer will be made from new plastics which would have high tensile strength, high resistance to scratches, and are colorful; while the inner layers would be made from recycled plastics.

2.3) Tertiary recycling can be separated into 2 categories: chemical recycling and thermolysis recycling.

2.3.1) Chemical recycling is the procedure to separate or split the chain structure of the polymer (depolymerisation) to gain monomers or oligomers when purified by using distillation and crystallization processes. The products achieved are high quality initial substances that can be reused to produce PET.

2.3.2) Thermolysis recycling: the PET structure can be separated or split by using heat, called as thermolysis. It is separated into 3 methods: pyrolysis, gasification, and hydrogenation.

– Pyrolysis is the procedure that breaks the polymer chain by using heat without the use of oxygen. The product obtained from the condensation process is in the form of liquid called as synthetic crude oil, which can be reused in the refinery. Those parts that did not condense would be reused as fuel to heat this process.

– Gasification is the procedure that breaks the polymer chain by using heat with the use of oxygen. This procedure occurs at a higher temperature than pyrolysis. The product gained is syngas, which is composed of carbon monoxide gas and hydrogen, which can be used as fuel directly. However, if it is separated in the forms of chemical substances, the value would increase 2-3 times. Hydrogenation is the technique adapted from the oil refinery process that uses catalysts. The PET polymer chain will separate or split due to heat and make contact with abundant hydrogen at pressure over 100 atm, causing absolute cracking and hydrogenation reactions. The main products obtained are liquid fuel, such as gasoline or diesel fuel.

2.4) Quaternary recycling: plastic can be combusted to be used as alternative fuel. The combustion of plastic gives similar calorific values as coal, which is 23 MJ/kg. It can be used to burn garbage, which would reduce the quantity of fuel required to incinerate waste. (MTECH, 2014)

In this research both primary recycling and mechanical secondary recycling were studied. The primary recycling is the recycling process of plastic scraps loss during the production process due to trimming or when the product does not meet the required standard; while mechanical secondary recycling is the recycling process of used plastic products that were sent back to be clean and grind for reuse. These two methods were chosen to compare the environmental impact and eco-efficiency values. The mechanical recycling process consists of many sub-processes (as shown in figure 2.9), which causes impact on many aspects of the environment. Such impacts include the collection of plastic drums and shipping, in which fuel is required in the shipping process which combusts and causes air pollution as well as global warming; or the cleaning process of contaminated plastic drums to be recycled requires water and various cleaning chemicals, which would cause waste water as well as Eutrophication phenomenon.

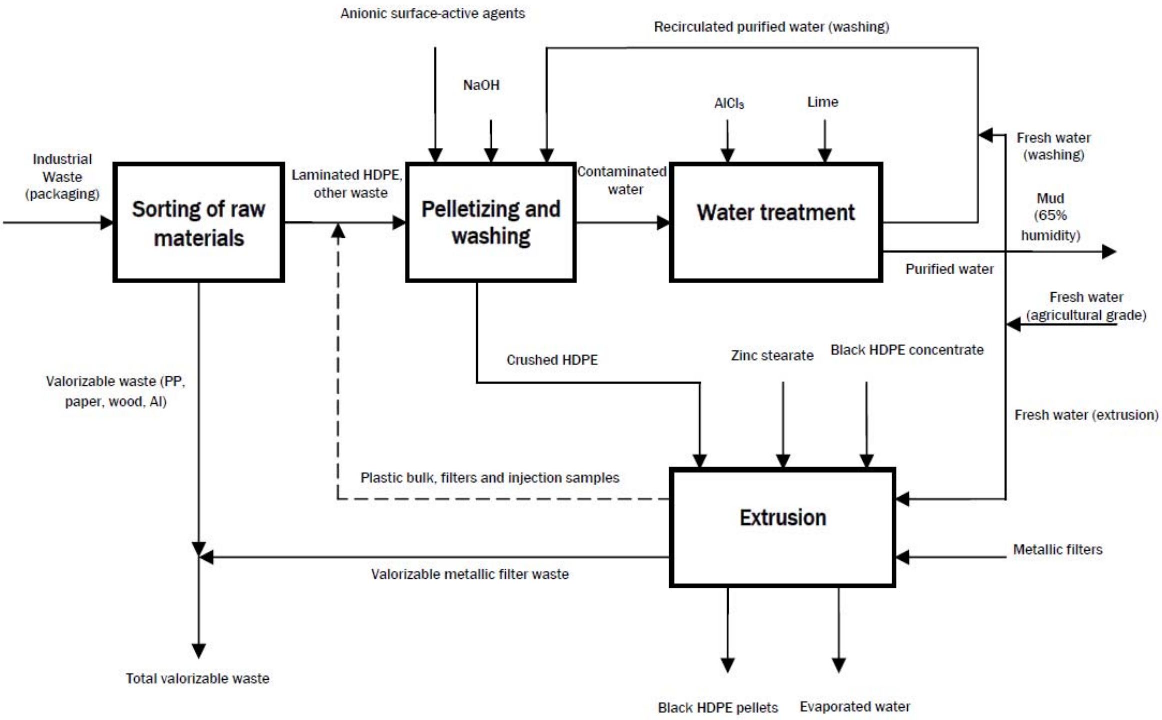

Figure 2.10 Production process of HDPE recycle pellets
(Garrain *et al*, 2008)

From the studies of franklin associates, a diversion of ERG prairie village, Kansas. (2011), which evaluated the energy and resource consumption and pollution discharge of the production process to produce 1 ton of recycled HDPE resins, it is found that the total energy consumption is 2,912 MBtu and total pollution discharge is 0.601 lb (as shown in table 2.14).

Table 2.14 Energy consumption and the waste emission from the production of recycled plastic HDPE.

Input			Output		
Raw material	Amount	Unit	Product and Co-product	Amount	Unit
Sorted postconsumer HDPE	1,079	lb	HDPE Recycle pellets	1,000	lb
100% sodium hydroxide	0.27	lb	Air pollution*	0.038	lb
Defoamant	1.52	lb	Solid waste**	79.1	lb
Surfactant	0.77	lb			
Alkaline cleaner	0.060	lb			
Energy for production	2,440	MBtu			
Energy for transportation	472	MBtu			
Water consumption	53.3	Gal			

Reference: FAL (2011)

Furthermore,Garrain *et al*. (2008) had studied the environmental impacts of the recycled resins production process by comparing the results with data from previous studies. The evaluation methods followed CML 2 baseline 2000 and the normalization factor of WesternEurope in 1995, resulting in table 2.15.

Table 2.15 Normalized eco-profile of 1 kg of HDPE (recycling or manufacturing)

Author	Abiotic depletion	GWP 100	Acidification	Eutrophication
Recycle industry	1.15E-14	5.82E-14	6.13E-14	8.06E-15
White *et al.*	3.63E-14	3.25E-13	4.10E-13	4.80E-14
Perugini *et al.*	1.38E-14	9.43E-14	1.15E-13	1.12E-14
Machinery industry	1.45E-14	9.89E-14	1.21E-13	1.18E-14
Buwal 250	2.04E-13	4.47E-13	4.47E-13	1.05E-13
Ecoinvent	2.08E-13	3.94E-13	7.83E-13	1.09E-13
PlasticsEurope	2.16E-13	3.91E-13	7.82E-13	1.04E-13

Reference: Garrain *et al.* (2008)

3) Plastic coloring

Colorants are additives that are mixed into plastic to beautify the product and to also help prevent deterioration due to sunlight. In addition, some colorants can also improve the crystallization of some thermoplastics.

Properties of colorants are that it must have the appropriate physical form, resistant to bleeding, highly resistant to paling due to sunlight, minimum effect on secondary processing, and resistant to external environment especially when they will be used for packaging.

3.1) Dyes

Dyes are organic components that have low molecular weight, and can dissolve and combine well in plastic. Color in polystyrene is caused due to the dissolution of color in the plastic. There is almost every color to choose from, it has high transparency and very high concentration of color, so it gives a very bright and colorful feel. Advantages of this type of coloring also include low specific gravity and can form bonds with plastilizers. However, most dyes have low resistance to sunlight, heat and chemicals. Dyes have various shades of color, ranging from bright colors to darker ones. The colors in this group include Nigrosine, or those in the Azo, Diazo, Perinon, Guilnoline, and Anthraquinone categories.

3.2) Pigments

Pigments are colors that do not dissolve in plastic but will disperse into small particles. Each type of pigment has different properties, even if they have the same shade of color; thus they cannot be used for the same type of application. Pigments can be divided into 2 types: organic pigments and inorganic pigments**.**

Most plastic packaging production processes use pigments due to the stability to heat and the ability to disperse well in plastic during the melting process. The applied ratio is 0.01% by weight.

For both dye and pigment procedures, both general and heavy metal chemicals are used in the production process. Thus, in order to ensure the safety of consumers, a maximum amount of the chemicals allowed in dye and pigment products are specified, as listed in table 2.16

Table 2.16 Maximum amount of metals in pigments and dyestuff

Material	Maximum (ppm)	
	Pigment	Dyestuffs
Arsenic	250	50
Cadmium	50	20
Chromium	100	100
Copper	-	250
Mercury	25	4
Nickel	-	200
Lead	100	100
Zinc	-	1000

Reference: Nimon and Behgin (1996)

2.2.3 Plastic drum production process

The plastic product industry is an end-industry of the petroleum industry, where the plastic parts production is as shown in figure 2.10. The main material used to produce plastic is various types of resins, depending on the requirements from the clients. Some factories may adjust the raw material by themselves by adding color or other additive chemicals. From then it is the mixture process, followed by melting to prepare for the formation process. There are various types of formation to achieve the product that is most suited for further application. Examples of types of formation include injection, extrusion, and blowing. After the formation process, the plastic piece would harden when the temperature decreases. Thus, cooling is required. After that it would be the procedure to beautify the work piece. Examples include trimming, color spraying, polishing or coating, and pattern printing. This would be the end of the plastic product formation process, and would be followed by the procedure to pack and deliver to customers.

Since there are many procedures for plastic formation, from studies it can be seen that by using different production procedures, the energy consumption per product weight would be different. By using the same production procedure and product but different raw materials, the energy consumption would also be different. Thus, the main factors that can show the difference in energy consumption for plastic industries are the production procedure and raw materials.

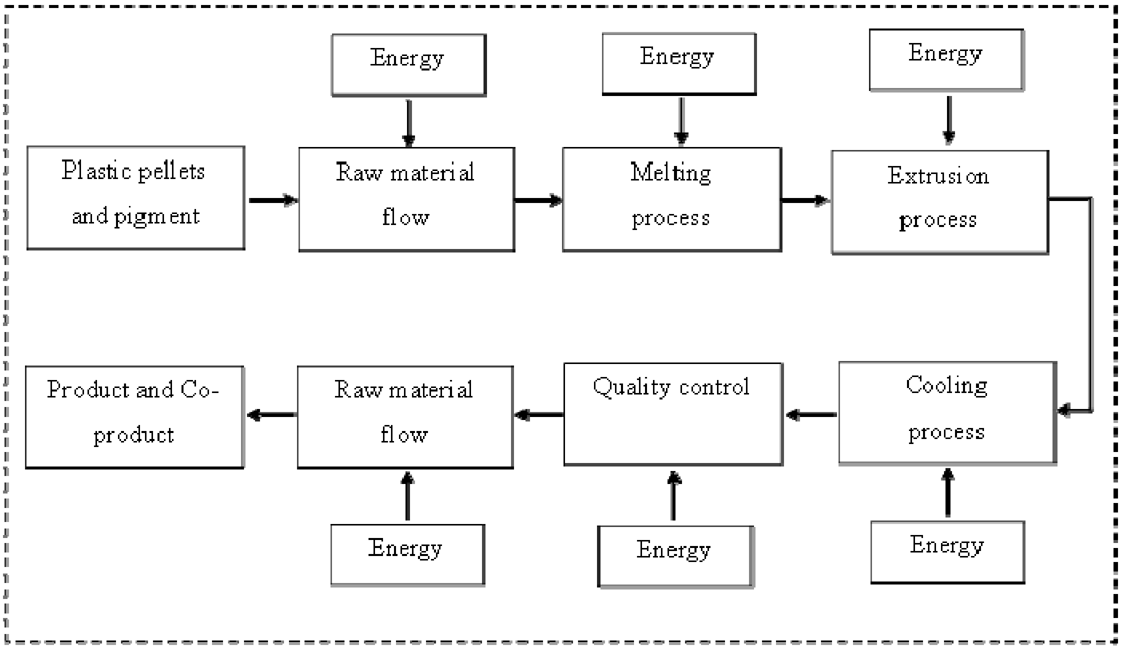

Figure 2.11 Energy consumption of plastic production (Ref)
(Petroleum Institute of Thailand, 2009)

The products produced from the extrusion blow molding process would mainly be plastic packaging products, such as engine oil bottle, oil tanks, shampoo bottles, fermented milk bottles, ink bottles, or plastic drums. These products account for 66% of the total amount of products produced by the extrusion blow molding procedure in 2008. (Petroleum Institute of Thailand, 2009)

2.2.3.1 Blow molding

The plastic production process by blow molding method is the molding of plastic products by melting resins in the extruder, by using heat from the electronic heater. Resins are the main product in this production process, and the most commonly used type is HDPE. From then the screw would compress the liquid plastic by the propulsion of the screw and the opening-closing of the mold by using hydraulics system. The compressed plastic would pass through the die head in a parison form. The mold would move to cover the plastic and compress air into the mold, blowing so that the plastic would expand fully in the mold. After that, cool water from the chiller would flow to cool the work piece so that it hardens according to the desired shape of the mold, as shown in figure 2.11.

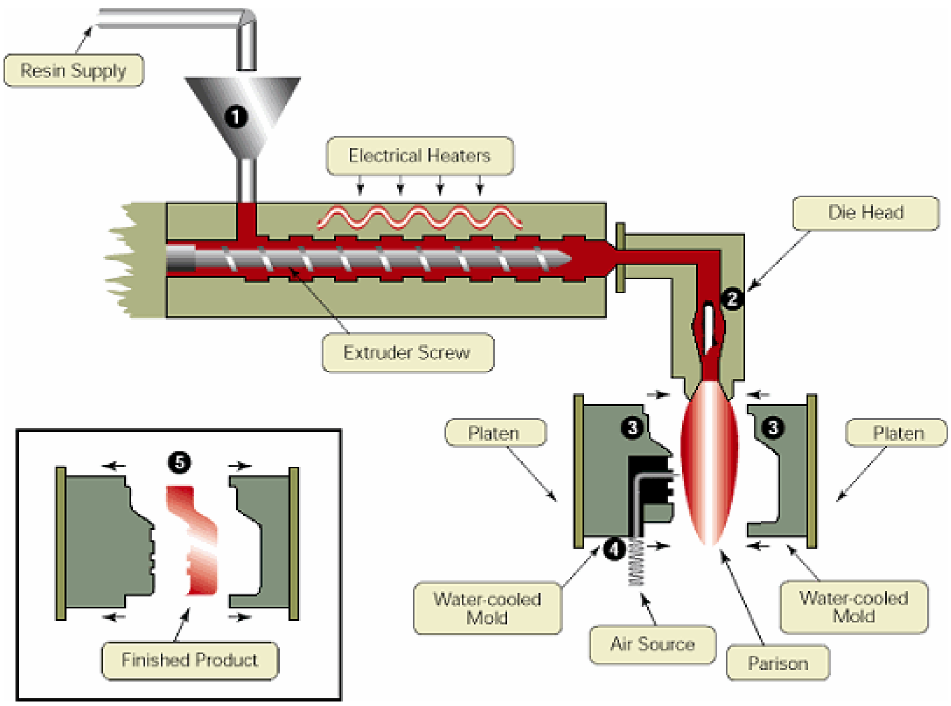

Figure 2.12 Production process of blow molding
(Department of Alternative Energy Development and Efficiency [DEDE], 2013)

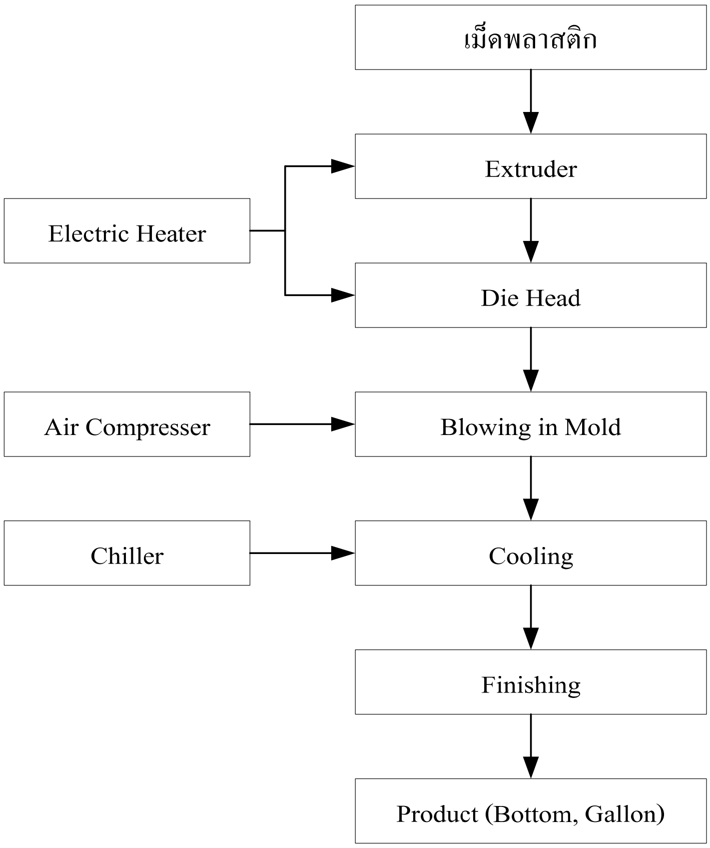

Figure 2.13 Flow chart of Blow molding production process (DEDE, 2013)

By studying the efficiency of energy consumption of the plastic bottle production process by using extrusion blow molding (EBM) method, it is found that the extrusion step is the step that consumes the highest amount of energy, up to 45% of the total amount of energy consumed by the entire process. (The Carbon Trust, 2010). Due to the fact that there are many plastic formation processes, and each process consumes different amounts of energy, the amount of waste discharged from the production procedure would also differ. The results of greenhouse gas emission from 2 types of processes to produce polyolefin products, which are blow molding and injection, show that the production process by blow molding emits a higher amount of greenhouse gas than that of injection method. For the production process to produce HDPE products by using the blow molding method, the greenhouse gas emission is 7.85±0.2 kg CO_2eq/kg; while by using the injection method, the emission is 2.30±0.02 kg CO_2eq/kg. (Soonthonchot, 2010)

From the studies on the life cycle of plastic products form by 2 different methods, which are blow molding and injection, it is found that blow molding method generates lower environmental impact, as shown in table 2.17.

Table 2.17 Production data of HDPE plastic drum by blow molding process

Input	Amount	Unit	Output	Amount	Unit
Fossil fuels	11.76	kg	VOC	100.454	g
Coal	8.575	kg	CO	291.882	g
Natural gas	2.834	kg	NO_x	1193.038	g
Petroleum	0.351	kg	SO_x	2618.289	g
Total Energy	13.596	mmBtu	CH_4	1521.84	g
			N_2O	14.887	g
			CO_2	1129300	g
			CO_2*	1130071	g
			GHGs	1172554	g
			PM10	1520.841	g
			PM2.5	399.732	g

Reference: Center for sustainable system (2012)

Apart from the life cycle and GHG emission assessment values of the product that can be evaluated from the acquisition of the raw materials and the various types of energy consumption in the production process, one important factor that affects the assessments is the environmental impact value due to shipping. Due to the fact that in each process there must always be relocation of materials from one point to another, thus energy consumption and fuel combustion due to shipping must be one factor that is also included in the life cycle and GHG emission assessments of the product.

2.2.4 Shipping

Shipping is considered to be one factor that influences the environmental impact since there is fuel combustion in the shipping process; both in the forms of gasoline or natural gas, which also causes greenhouse gas.

From the studies on the life cycles of 2 plastic bottle sizes in Europe and Northern America, it can be found that the carbon discharge value only for the production and distribution processes account for more than half of the total discharge for the entire process. The discharge value was 77.4% in Europe and 68.3% in Northern America, as shown in table 2.18.

Table 2.18 The GHG emissions in the manufacturing process of plastic bottles.

Process step	Europe (1.5 L bottle)		North America (500 ml bottle)	
	g CO_2(eq)	(%)	g CO_2(eq)	(%)
PET bottle	60.8	38.0	31.0	38.8
Distribution transportation	63.1	39.4	23.6	29.5
Corrugated tray	18.0	11.2	4.5	5.6
Production electricity & natural gas	8.5	5.3	4.1	5.1
Cap.	2.7	1.7	2.7	3.4
Electricity for consumer cooling	2.4	1.5	2.0	2.5
Label adhesive	2.3	1.4	2.3	2.8
Retail electricity & natural gas	2.1	1.3	10.0	12.5
Others	01	0.1	-0.1	-0.1
Total	160	100	80	100

Reference: Beverage industry environmental round table, (2012)

The important factor that causes high greenhouse gas discharge during the shipping process is the shipping distance for each scope of study. The distance is in direct proportion with the amount of greenhouse gas discharged, where longer distance would always cause for a higher greenhouse gas emission.

Shen, (2011) compared the life cycles of polylactic acid (PLA) and polyethylene terephthalate (PET), and found that the shipping distance was the significant factor that caused the difference between the carbon dioxide discharge values of the two types of plastic. The distance in the life cycle of PET is 5 times higher than the distance in the life cycle of PLA, causing for the significant difference between the carbon dioxide discharge values (as shown in table 2.19).

Table 2.19 The GHG emissions from the transportation distance.

Travels	PLA			PET		
	Distance (km)	Fuel (liters)	CO_2 (tons)	Distance (km)	Fuel (liters)	CO_2 (tons)
R/M to producer	1,060	9.53×10^2	0.26	6,500	1.63×10^6	1,200
Producer to retailers	2,800	9.33×10^2	0.69	9,900	2.48×10^6	1,800
Consumer to disposal	80	27	0.02	80	27	0.02
Total	3,940	1.31×10^3	0.97	16,480	4.11×10^6	3,000.02

Reference: Shen (2011)

Greenhouse gas discharge during the shipping process is considered to be a rather significant part for the life cycle assessments of plastic drums, especially for recycled ones. This is due to the fact that the shipping process would have to cover from the procedure to collect used drums from consumers until the delivery to the recycling company. Thus, the shipping procedure is another important factor in assessing the eco-efficiency.

From the comparison of the energy consumption for the plastic bucket production process between using 100% pure resins and 100% recycled resins, it is found that the recycled resins production procedure has lower energy consumption in the production process than pure resins, but the energy consumption in the shipping process is higher (as seen in table 2.20).

Table 2.20 Energy consumption of virgin and recycle process

Process	Product manufacture using 100% virgin inputs ($MTCO_2eq$/Short Ton)	Product manufacture using 100% recycle inputs ($MTCO_2eq$/Short Ton)	Difference ($MTCO_2eq$ /short ton)
Process Energy	1.72	0.13	-1.59
Transportation Energy	0.04	0.05	0.01
Process Non-energy	0.19	0.00	-0.19

Reference: PlasticsEurope, (2005)

2.2.5 Application procedure

Application means the procedure in taking plastic drums from the production section to load the desired goods or products. There are 3 main steps in this procedure, which are the energy and resource consumption values in the storing, shipping and application processes.

This research studies cradle-to-gate (C2G) or business-to-business (B2B) processes, so the GHG emission in this step would not be calculated.

2.2.6 Product management procedure after use

Product disposal is the procedure to manage the products after use, in which there are various methods to use; such as incineration, landfill, or recycling. Each method in exterminating waste causes different greenhouse gas discharge values.

Craighill and Powell (1996) assessed the life cycle of HDPE by landfill and recycling methods, and found that the environmental impact value in the aspect of causing global warming for the landfill method is higher than that of recycling. The impact value was 159.2 kg/t and 31.22 kg/t, respectively.

This research studies Cradle-to-Gate (C2G) or Business-to-Business (B2B) processes, so the GHG emission in this step would not be calculated.

2.3 Eco-efficiency assessment

2.3.1 Eco-efficiency assessment

The economy growth in the industry field and the increase in number of industry factories directly affect the ecology and environmental system. It affects the resource and energy consumption, pollution caused from the materials used, pollution from the production process, shipping process as well as waste discharge, and disposal of remains from the production process. The course to fix the pollution problem caused from industries nowadays focus on fixing the problem at the end results, which are monitoring the environmental impacts in nearby areas, as well as using new treatment technologies with the waste caused from the industrial sector before it is discharged to the ecology and environmental system. The aforementioned course in fixing the problem usually causes an increase in the production cost and product price, which does not lead to a sustaining development for the industrial sector.

The course and direction for a sustaining development in the industrial sector can be built by considering the significant main element, which is to create equilibrium between the advance in economics and the protection of the ecology system at the same time. This element is very important. The principle in creating economical wealth is to use the method in increasing the efficiency of resource consumption and reducing the pollution discharge. The aforementioned principle in creating equilibrium was applied to be a theoretical principle, called as "Eco-efficiency".

The application of the advance in technology allows for the continuous economic development; and if it could go simultaneously with the reduction in environmental impact in the aspect of efficiently using resources and reducing pollution occurring, it would lead to sustaining development. In other words, the aforementioned principle can be used as a tool to manage the business sectors to have the ability to compete economically as well as joint responsibility on the impact caused to the natural resources and environment in this world. The word eco-efficiency was first used and spread by 2 Swiss researchers in 1990. Shortly after, the World Business Council for Sustainable Development (WBCSD), which is an assembly of more than 130 international leading companies from 30 countries around the world, officially defined the word of eco-efficiency in 1991 under the thought of integrating the improvements in the economy and environment. This will further lead to results due to the sustaining development.

2.3.1.1 Meaning of Eco-efficiency

The foundation on the meaning of eco-efficiency comes from the situation in which the amount of resource remaining is inadequate with the increasing consumption rate nowadays, creating increasing competition between business organizations and industries. There is a change in the competition format; from focusing on strategies to design and develop products and produce goods or services to conquer competitors only, now the competition during this new oppressing situation covers the details as follows:

– Reducing the resource consumption is the attempt to reduce the consumption of the initial materials in the production process, as well as energy, water and land. It also promotes the reuse and recycling of the products.

– Reducing the impact on nature is to reduce the amount of waste discharged into the environment, which are waste water, garbage, and poisonous substances.

– Increasing product or service value is the attempt to maximize the benefits that the consumers would receive from the goods and services, while minimizing the impact on the environment and natural resources.

The rules of the new competition cause for the eco-efficiency concept to occur. The word comes from the combination of the words ecology and economy, with the word efficiency. Thus, eco-efficiency means to increase the competition potential for business sectors, along with the increase in responsibility in natural resources and the environment.

The concept in increasing eco-efficiency was launched by the World Business Council for Sustainable Development (WBCSD), which is the assembly of international leading companies. It was also officially accepted in the Earth Summit in 1992. WBCSD has specified 7 methods to successfully manage the business in the aspect of eco-efficiency, as follows.

– Reduce resource or material consumption in the production and service processes

– Reduce energy consumption in the production and service processes

– Reduce the amount of pollution discharged to the environment

– Reinforce the potential in reusing materials

– Promote the use of renewable resources

– Increase the life span of the product, and

– Increase the service level of the product and reinforce the service business

The aforementioned eco-efficiency concept is suitable for the business sector since it creates the equilibrium between the progress in business that emphasizes on the increase in profit for the organization, and the preservation of the ecology system by simultaneously reducing the environmental impact. In addition, it is also the index to indicate the relationship between the economy and environment that aims for sustainable development, which is the overall target in the long-run for various countries**.**

WBCSD divided the applicable indicators that are used to calculate the eco-efficiency into 2 categories:

1) General applicable indicators

This type of indicator is used for businesses in general. It can truly be applied to every business and is accepted in the international level. Each indicator is related to an international environmental problem. The general applicable indicators used for the product or service value include the quantity of the product or service produced and provided to customers, or the total sales amount. On the other hand, the general applicable indicators used for the environmental impact include the energy and resource consumption, water consumption, waste and pollution discharge amount that affects the greenhouse gas situation and ozone quantity.

2) Business specific indicators

These indicators are those that the business sector can choose to calculate the additional eco-efficiency values other than the general applicable indicators, which will help for that business to increase the success in sustainable development. This type of indicator will be considered from the particularities of each business. Examples of this type of indicator are the gross margin value, amount of landfill waste, and amount of incinerated waste.

2.3.1.2 Benefits from increasing eco-efficiency

The details of the benefits from increasing the eco-efficiency are as listed below.

1) Business, trade, and marketing fields

1.1) Evaluates the condition of the product, organization or business sector in previous periods of time. It can be compared with the management capability of other organizations or business sectors in the same category (Benchmarking), which would lead to an increase in the production efficiency of organizations or business sectors.

1.2) Results obtained from the eco-efficiency assessment can be used to improve the efficiency of their own products.

1.3) Reduce the production costs, in terms of both energy and resource consumption.

1.4) Can be used to determine the strategy policies of the organization or business sectors for future management.

1.5) Increase the production efficiency, or in other words, increase the potential in competition of the industry.

1.6) Can be used as the marketing strategy and promote the image of the company in being the leader in terms of developing and producing products that are environmentally friendly.

2) Environmental field

2.1) Reduce the environmental pollution, such as reducing the resource consumption and increasing the use of renewable resources, and reducing the amount of pollution discharged.

2.2) Creates sustainable consumption of resources.

2.3.1.3 Procedures to increase the eco-efficiency

Eco-efficiency can be calculated from the ratio between the performance and the environmental impact of the product, as shown in Equation (5).

$$\text{Eco-Efficiency} = \frac{\text{Performance}}{\text{Environmental impact of product}} \qquad (5)$$

Where Eco-Efficiency is Eco-efficiency of product consider
Performance is Performance of product consider
Environmental impact is Environmental of product consider

There are many aspects to the performance and environmental impact of the product, depending on the objective of the assessor. Examples of the different aspects in the performance and environmental impact assessment are shown in table 2.21.

Table 2.21 Performance and Environmental impact of products

Performance	Environmental Impact
Quantity	GHG Emission
Net sales	Energy Consumption
Value	Material Consumption
Long life	Water Consumption
Aesthetic Safeness	Land Use
Convenience	Toxicity

Reference: Charmondusit and Keartpakpraek, 2011)

As for the eco-efficiency assessment for business and industry sectors, generally it is the calculation to find the ratio between the product or service value and the environmental impact. It mainly considers the consumption of energy, materials and water, and the emission of greenhouse gas and carbon dioxide (CO_2).

In order to increase the eco-efficiency in business and industry sectors, the quality of the product or service must be improved, as well as the impact on the environment must be minimized. Pictures 1 and 2 are examples of the eco-efficiency execution of two major companies in Japan: Toyota and Toshiba.

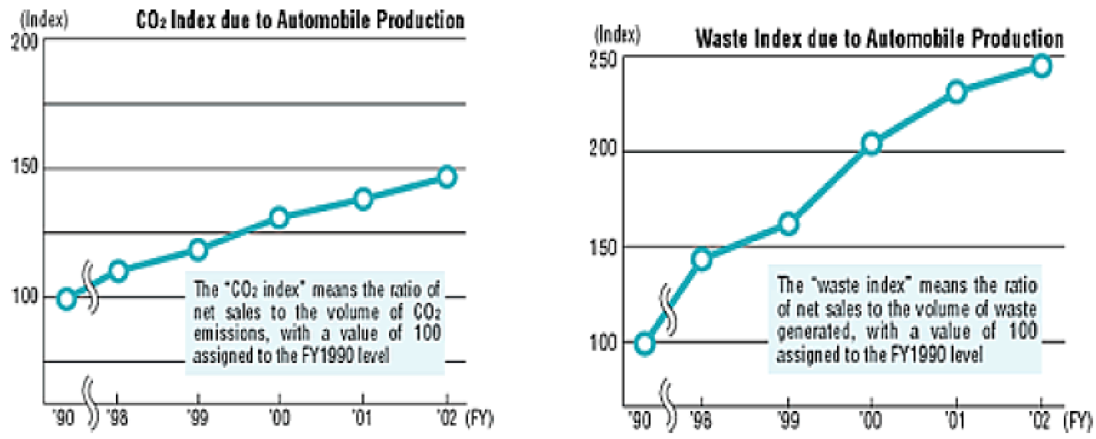

Figure 2.14 Eco-efficiency assessment of TOYOTA product

(MTECH, 2013)

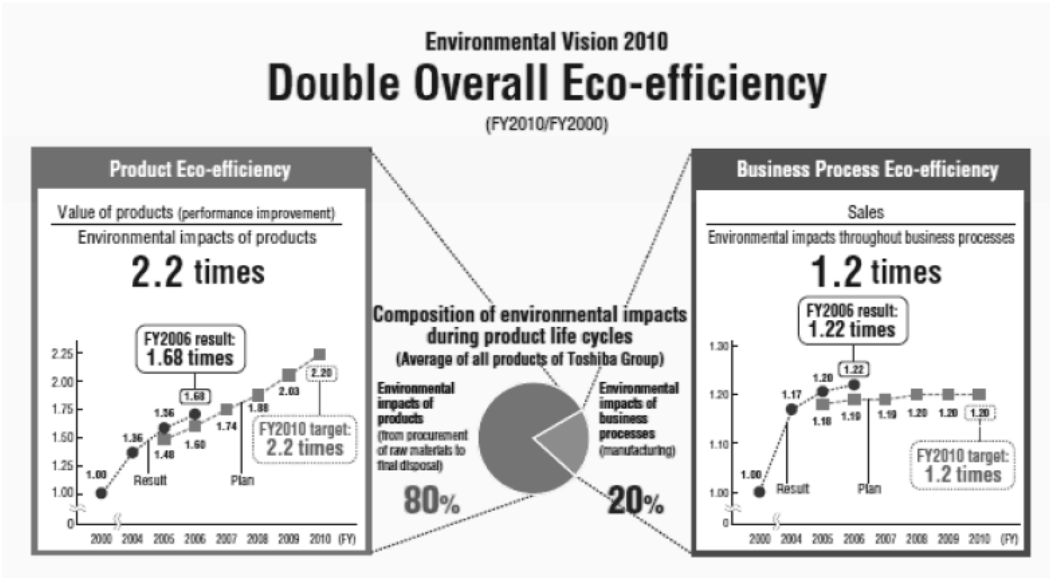

Figure 2.15 Eco-efficiency assessment of TOSHIBA product

(MTECH, 2013)

2.3.1.4 Meaning of factor

By assessing only the eco-efficiency of the product, service or organization, it does not cause any benefits in the development, improvement, increase in efficiency, or even the increase in sales, if the product, service or organization does not give any importance to the factor.

In this case, factor is the ratio between the eco-efficiency of the product subject to assessment and the eco-efficiency of the benchmark product. Generally, the benchmark product is mostly the base line model or a previous model.

The factor obtained from the calculation may be any number, depending on the capability in developing and improving of said organization. This is the reason why this factor is mostly known as Factor X, with X representing any number calculated by comparing the eco-efficiency value from the interested year with the base year. For instance, the factor in 2006 for Toshiba was 1.68, when the year 2000 was chosen as the base year.

When examined further on, it can be seen that companies also determine the target of the development of their own products by specifying that in 2010, the production efficiency would increase 2.2 times when compared to the base year. If the company can achieve this, it signifies that the company can reduce the environmental impact alongside with the increase in product value up to 2.2 times compared to the base year. This data can also be used for marketing and public relations schemes. Apart from factor X, another word that should be known is Factor 4, which is a fundamental conceptual framework that was proposed in 1998. It is based on the hypothesis that the “resource productivity” must increase 4 times, which means that the quality of the product produced must be doubled while the resource consumption must be reduced to half of the original value. This would all lead to sustainable development**.**

Furthermore, some stages would also mention Factor 10, which thinks that in order to lead to sustainable energy, developed countries must make the eco-efficiency to be 10 times the base value, since in these countries the resource consumption is higher than developing countries or underdeveloped countries.

2.3.1.5 Results from the eco-efficiency assessment

The report for the eco-efficiency assessment should consist of:

1) Organization profile the name of the assessed organization, type of business, product or goods produced, number of employees in the organization, and general information related to the organization, such as address, contactable websites, or the year of establishment.

2) Product and service value profile such as the total value of product sales or the total power in producing goods.

3) Environmental profile includes the environmental impact data obtained from the general applicable indicators and business specific indicators, such as water and energy consumption, and initial material quantity.

4) Results of eco-efficiency ratio calculation obtained from each type of indicator.

5) Methodological information refers to the details of the study procedures used to assess the eco-efficiency as well as the various methods to choose the types of indicator.

2.3.1.6 Tools related to increasing the eco-efficiency

In the assessment of eco-efficiency, there is a necessity for the application of environmental tools in both the aspect of impact and the development of the product after learning the environmental capability of the product or business. The significant tools in the eco-efficiency assessment include:

1) Life Cycle Assessment (LCA)

LCA is the technique used to analyze and evaluate the quantitative environmental impacts of the product, production process, or other related activities. The entire life cycle would be considered, from the acquisition of the raw materials, production process, shipping, application/maintenance, reuse as well as recycling, and also disposal after the useful life. In other words, it can be said that the product would be considered from cradle to grave.

2) Cleaner technology (CT)

CT is the continuous development of the production, service and consumption processes by causing minimum impact and risk to humanity and the environment. It must also be economically worthwhile, which can be done by reducing the pollution at the source, reuse and/or recycling, that receives cooperation from everyone in the organization.

3) Economic and ecological design (Eco-design)

Eco-design is the procedure that appends the economic and environmental concepts with the product designing step. The entire product life cycle would be considered, from the product development planning step, designing period, production, application, and extermination or disposal periods. It would reduce the capital of every step in the product development process, as well as simultaneously reducing the environmental impact. This would benefit the business, community, and environment, which is the course that leads to sustainable development.

Craighill and Powell (1996) evaluated the economic value environmental impact of 7 types of materials; which are paper, aluminum, iron, glass, PET, HDPE, and PVC. By comparing the disposal methods between landfill and recycling, it was found that recycling created a higher net value over product weight ratio than landfill for 4 types of materials: aluminum, glass, paper and iron. However, it was not environmentally worthwhile for the three types of plastic: HDPE, PET and PVC, which resulted in the net value over product weight ratios for 1 ton of plastic to be -2.57, -7.28, and -4.10 £/t, respectively (as shown in table 2.22).

Table 2.22 Economic valuation of external costs with the kerbside scheme

Material	Waste disposal (£/t)	Recycling (£/t)	Net benefit from recycling (£/t)	Net benefit excluding congestion (£/t)
Aluminum	1880.27	111.41	1768.86	1771.84
Glass	254.78	67.20	187.58	189.96
Paper	299.85	73.79	226.07	228.42
Steel	269.40	31.64	237.76	240.26
HDPE	9.49	12.07	-2.57	-0.21
PET	13.98	21.25	-7.28	-4.05
PVC	7.46	11.55	-4.10	-1.57

Reference: Craighill and Powell (1996)

From the report it can also be seen that the HDPE recycling process causes a negative impact on the economic worthwhile. In other words, it is not economically worthwhile, calculated to be -2.57 £/t. This is due to the shipping procedure, that at equivalent shipping capacities (1 trip/truck), plastic is lighter in weight so when compared in the unit of weight per weight, the environmental impact caused would be higher than that of other types of materials.

2.3.2 Pollution prevention cost

Pollution prevention cost is the marginal prevention cost that is directly proportioned to the quantity of pollution created in each aspect. That is to say, the production process that causes high amounts of environmental impact would naturally increase the pollution extermination cost, since capital is required to manage the pollution level to meet the normal conditions following the standards of each country. However, due to the fact that each aspect of the environmental impact requires different types of management measures; the capital cost in each aspect of pollution management would be different. Vogtlander (2001) evaluated the pollution preventive cost as listed in table 2.23.

Table 2.23 Pollution prevention cost of midpoint level

Prevention of impact	Unit	Value	
		Euro (€)	Dollar($)
Global warming	kg CO_2-eq	0.114	0.157
Acidification	kg SO_2-eq	6.40	8.83
Eutrophication	kg PO_4^{3-}	3.05	4.21
Summer smog	kg VOC-eq	12.30	16.97
Winter smog	kg fine dust	50.00	69.00
Heavy metals	kg ZN-eq	680	938
Carcinogenics	kg PAH-eq	12.30	16.97

Reference: Vogtlander (2001)

As for the pollution preventive cost for each type of production or service process, it can be calculated from the product of the capital of pollution management and the quantity of pollution in each aspect. The pollution preventive cost for each type of production or service process is the total sum of the pollution preventive costs of each aspect, following the equation:

Pollution prevention cost = ∑ (Environmental impact X Marginal prevention cost)

Where Pollution prevention cost is pollution prevention cost of product
Environmental impact is environmental midpoint impact of product
Marginal prevention cost is marginal cost of product

2.4 Related research

Craighill and Powell (1996) evaluated the life cycle and economic value of the recycling process of 7 types of materials; which are paper, aluminum, iron, glass, PET, HDPE, and PVC. The disposal methods between landfill and recycling were compared between 3 aspects of environmental impacts, which are global warming, acidification, and Eutrophication. It was found that even though disposing plastic waste by recycling would cause less environmental impact in the aspect of global warming than disposing by landfill, but it would cause higher impact in the aspects of acidification and eutrophication due to the shipping and cleaning processes, as listed in table 2.24.

Table 2 .24 Environmental impact comparison of HDPE waste between disposal and recycle

Contribution	Unit	Waste disposal	Recycling
Global warming	CO_2 equivalent (kg/t)	159.2	31.22
Acidification	H+ equivalent (kg/t)	80.92	91.31
Eutrophication	Phosphate equivalent (kg/t)	0.18	0.22

Reference: Craighill and Powell (1996)

FAL, (2011) studied the life cycles of HDPE and PET resins, covering from the collecting process, the sorting and re-grinding processes, until recycled resins are achieved. The Global Warming Potential (GWP) would then be assessed. It was found that both types of recycled plastic cause less impact when compared to pure resins, as shown in table 2.25.

Table 2.25 Global warming impact of Virgin and Recycle HDPE pellets

Process type	Global warming potential (lb CO_2-eq)	
	HDPE	PET
Virgin pellet	1,822	2,746
Cut-off, weight-base collection	628	796
Cut-off, volume-base collection(50% compaction)	696	846
Open-loop, weight-base collection	1,225	1,771
Open-loop, volume-base collection(50% compaction)	1,259	1,796

Reference: FAL (2011)

This is consistent with the research from WRAP, (2010) that compared the environmental impacts of HDPE bottles produced from pure resins and recycled resins at different ratios in the United Kingdom. It was found that plastic bottles made from every ratio of recycled resins caused less environmental impact compared to plastic bottles made from pure resins in every aspect that was evaluated (as shown in table 2.26). This is consistent with the same comparative research on the environmental impact of HDPE bottles in China, that resulted in plastic bottles made from recycled plastic having a lower impact on the environment when compared to plastic bottles made from pure resins (as listed in table 2.27).

Table 2.26 Impact assessment result for the HDPE bottle scenario with recycling in the UK as the waste management option (per functional unit)

Impact category	Unit	HDPE bottle 100% virgin ,recycling UK	HDPE bottle 30% recycled, recycling UK	HDPE bottle 50% recycled, recycling UK	HDPE bottle 30% recycled, 10% light weight, recycling UK
Abiotic resource depletion	kg Sbeq	0.345	0.344	0.344	0.326
Climate change	kg CO_2eq	35.6	35.5	35.4	34
Photo-oxidant formation	kg C_2H_4eq	0.0363	0.0363	0.0362	0.0335
Acidification	kg SO_2eq	0.00527	0.00517	0.0051	0.0054
Eutrophication	kg PO_4^{3-}eq	-0.0484	-0.0489	-0.0493	-0.0404
Human toxicity	kg 1,4-DBeq	4.13	4.12	4.11	4.01
Human aquatic eco-toxicity	kg 1,4-DBeq	0.753	0.752	0.752	0.719

Reference: WRAP (2010)

Functional unit = 15,500 g.

Primary packaging	14,426.6 g.
Packaging for delivery to dairy	822.0 g.
Packaging for delivery to retail	268.6 g.

Table 2.27 Impact assessment result for the HDPE bottle scenario with recycling in the China as the waste management option (per functional unit)

Impact category	Unit	HDPE bottle 100% virgin ,recycling China	HDPE bottle 30% recycled, recycling China	HDPE bottle 50% recycled, recycling China	HDPE bottle 30% recycled, 10% light weight, recycling China
Abiotic resource depletion	kg Sbeq	0.365	0.0364	0.364	0.345
Climate change	kg CO_2eq	38.6	38.6	38.5	37.1
Photo-oxidant formation	kg C_2H_4eq	0.0406	0.0406	0.0405	0.0378
Acidification	kg SO_2eq	0.0111	0.0110	0.0109	0.0112
Eutrophication	kg PO_4^{3-}eq	0.0138	0.013	0.013	0.0218
Human toxicity	kg 1,4-DBeq	5.86	5.85	5.84	5.74
Human aquatic eco-toxicity	kg 1,4-DBeq	0.784	0.783	0.783	0.750

Reference: WRAP (2010)

Nevertheless, it is not consistent with Simoes *et al.* (2011) that studied the life cycle of pure and recycled HDPE plastic products by using 5 different Normalization and Weighting score methods. It was found that each assessment method caused for different environmental impact values, but the tendency of the results were in the same direction. Recycled resins were able to reduce the resource consumption amount in the production process higher than that of pure resins since they were reusing already produced products. However, it was found that recycled resins have a higher pollution emission rate than pure resins in every aspect, such as air and water pollutions and dangerous solid contamination (as shown in table 2.28).

In addition, when the results obtained were assessed to find the environmental impact, it was found that recycled resins cause impact on the environment higher than that of pure resins in every aspect. Thus, using recycled resins could cause greater environmental impact than using pure resins (as shown in table 2.30).

Table 2.28 Contribution of the difference compartments to the single score of the two system in each of the LCIA methods studied

Compartment	EPS 2000 (mPt)		EI 99 (mPt)		EI 95 (mPt)		EDIP 97 (mPt)	
	Current AGL	Optional AGL	Current AGL	Optional AGL	Current AGL	Optional AGL	Current AGL	Optional AGL
Resources	2660	2266	409	90.2	-0.16	-0.15	7.20	7.11
Gas emissions	1110	1530	193	270	10.1	16	13.10	36.90
Liquid emission	-0.03	-0.40	6.72	15.20	2.82	5.37	14.30	47.40
Solid emission	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.24

Reference: Simoes *et al.* (2011)

Table 2.29 Environmental impact assessment of HDPE virgin

Impact categories	Current AGL		
	EI 95	CML 2	EDIP 97
Climate change (kg CO_2)	6.52E+00	6.88E+00	7.03E+03
Ozone layer depletion (kg CFC-11)	2.61E-06	1.97E-06	1.97E-06
Summer smog (kg C2H4)	1.19E-02	1.57E-03	1.17E+01
Acidification (kg SO2)	4.36E-02	4.19E-02	4.36E+01
Eutrophication (kg PO4)	4.14E-03	4.14E-03	4.16E+01

Reference: Simoes *et al*. (2011)

Table 2.30 Environmental impact assessment of HDPE recycle

Impact categories	Optional AGL		
	EI 95	CML 2	EDIP 97
Climate change (kg CO_2)	7.97E+00	8.34E+00	8.42E+03
Ozone layer depletion (kg CFC-11)	5.97E-06	4.74E-06	4.74E-03
Summer smog (kg C_2H_4)	1.22E-03	3.53E-03	2.64E-01
Acidification (kg SO_2)	7.77E-02	8.40E-02	7.78E+01
Eutrophication (kg PO_4)	3.46E-03	3.46E-03	3.48E+01

Reference: Simoes *et al*. (2011)

Britta (2005) comparatively studied the life cycles of 2 types of plastic bottles, which are polyethylene terephthalate (PET) and High Density Polyethylene (HDPE) plastic bottles. The resource and energy consumption values, as well as the waste discharge to the environment, were compared by using the SimaPro 6.0 program following the Eco-indicator 99(I)V2.1/Europe EI 99 I/I method. The results are as shown in Table 2.31: Impact from the production processes of HDPE and PET plastic bottles.

Table 2.31 Environmental impact assessment of HDPE and PET bottle production

Impact inventory	Emission value (mPt) by weighting score	
	HDPE bottle	PET bottle
Carcinogens	0.49	4.99
Resp. organics	0.35	-1.94
Resp. inorganics	151.86	0.47
Climate change	85.75	42.89
Radiation	0.00	0.03
Ozone layer	-0.01	-0.02
Ecotoxicity	0.05	0.63
Acidification/Eutrophication	9.27	-0.70
Land use	0.00	0.85
Minerals	24.07	85.92

Reference: Britta. (2005)

Parker (n.d.) studied the carbon footprint of plastic containers and found that different sizes would cause for different environmental impact values. From the study of the energy consumption in the production process of 3 different HDPE container sizes, which are 25, 220, and 1000 kilograms, it was found that the total energy consumption in producing a 25 kilogram-sized container is 1,702 MJ and the greenhouse gas discharge value is 102 kg CO_2eq. On the other hand, the total energy consumption in producing a 1,000 kilogram-sized container is 214 MJ and the greenhouse gas discharge value is 13 kg CO_2eq (as shown in table 2.32).

Table 2.32 Greenhouse gas emissions in different size of packaging

Packaging size	Energy use per tonne of product (MJ)	Carbon footprint per tonne of product (kg CO_2-eq)
25 kg keg	1702	102
220 kg Drum	1215	73
1000 kg Bulk container	214	13

Reference: Parker (n.d.)

Muthu *et al.* (2011) comparatively studied the greenhouse gas discharge values from the utilization of HDPE bags of residents in China and Hong Kong, with the utilization in India. It was found that the amount of plastic bags utilized in India is approximately 7 times lower than the amount utilized in China and Hong Kong, due to the fact that there is more reuse of plastic bags in India. The amount of plastic bag reuse in India is 55%, while for China and Hong the reuse value is at 46% and 42% respectively. Thus, this would lead to a lower greenhouse gas emission in India compared to China and Hong Kong. The greenhouse gas emission value in India is 1.93 kg CO_2eq/kg of plastic bag, while for China and Hong Kong, the value is 1.94 kg CO_2eq/kg of plastic bag (as shown in table 2.33).

Table 2.33 GHG Emission data of HDPE plastic bag production

Inventory data	Unit	China & Hong Kong	India
Weight/bag	g	6	6
Bage/year	bag	1095	150
Material consumption	kg	6.57	0.9
Primary energy	MJ	442.2	60
GHG Emission per unit	kg CO_2eq	12.8	1.74
GHG Emission per weight	kg CO_2eq/kg	1.94	1.93

Reference: Muthu *et al*. (2011)

In the Unites States, Greene (2011) studied the life cycles of single-use HDPE plastic bags and reusable paper bags. It was found that HDPE plastic bags has approximately 3 times higher greenhouse gas emission that reusable paper bags (as shown in table 2.34).

Table 2.34 Life cycle inventory for 1500 plastic bags and 1000 paper bags

Inventory data	Unit	1500 Plastic Bag industry average	1000 Paper Bag (30% recycled)
Weight/bag	g	6	52
Bags/year	bag	1500	1000
Material consumption	kg	15	23
Primary energy	MJ	763	2,622
GHG Emission per unit	kg CO_2eq	40	80
GHG Emission per weight	kg CO_2eq/kg	4.44	1.54

Reference: Greene (2011)

Furthermore, DECCW (2010), had also studied the efficiency of using many types of recycled materials, including HDPE plastic. It was found that by using recycled plastic, it could reduce the environmental impact and energy consumption in various aspects, such as reduction in greenhouse gas emission, reduction in energy consumption, and reduction in hazard solids. The only exception is the water consumption, which increases due to the cleaning procedure so that the products could be reused. Nevertheless, the overall picture shows that the recycling process can reduce the environmental impact, as shown in table 2.35.

Table 2.35 Net benefit of recycling 1 tonnes of waste material

Impact	Unit	Kerbside	C&I, C&D
Greenhouse gases	tonnes CO_2eq	0.84	1.08
Cumulative energy demand	GJ LHV	50.35	57.92
Water use	kL	-3.31	-3.58
Solid waste	tonnes	2.55	2.84

Reference: DECCW (2010)

Soonthonchot (2010) studied the greenhouse gas emission from the polyolefin production process of High Density Polyethylene (HDPE) and Polypropylene (PP) that was formed by using blow molding and injection methods to produce plastic bottles and lids. The SimaPro program version 7.1 was used, and the study considered the resins from before the formation process until they were molded into products. It was revealed that the formation by using blow molding method causes higher greenhouse gas emission than injection method. The emission values for PP and HDPE by using blow molding method are 10.7±0.32 and 7.85±0.20 kg CO_2eq, respectively. As for the emission values for PP and HDPE by using injection method, the values are equal to 2.42±0.03 and 2.30±0.02 kg CO_2eq, respectively.

CHAPTER III
METHODOLOGY

3.1 Goal and scope definition

3.1.1 Study goal

This research aimed to study life cycle 2 types of 20-liter HDPE plastic drum including plastic drum from primary recycled pellets and plastic drum with secondary recycled plastic pellets as the composition. This research evaluated 2 processes including obtainment of material (upstream process) and production (core process) which did not cover product distribution process, usage and waste disposal to compare the environmental impact and production cost of each plastic drum type. It was conducted as the guidelines to reduce environmental impact and it was most suitable with production cost of the plastic drum manufacturer with least environmental impact.

3.1.2 System boundary

The system boundary of this research was the obtainment and production process of 20-liter plastic drum (approximate weight of 1 kilogram) produced by a plastic drum manufacturer in Khaoyoi District, Petchburi Province. The process of Extrusion blow molding with “TONGDA MACHINERY” plastic making machine Model TDB-25A consumed electricity for 42 kilowatt/ hour with average capacity of plastic production for 2 tons a day.

The format of evaluation in this research was business-to-business (B2B) consisting of 2 processes including 1) pollution release from upstream process such a obtainment of materials in plastic drum production process and 2) pollution release from core process such as plastic drum production etc. Furthermore, environmental impact assessment was conducted in both midpoint and endpoint according to the evaluation model of ReCiPe 2008 and the derived data from such impact assessment would be used to evaluate eco-efficiency.

3.1.3 Functional unit

Functional unit is a 20 liter of HDPE plastic drum with approximate weight of 1.1 kilogram is made of pure plastic pellets mixed with recycled plastic. It is used to contain chemicals and it is moderately or slightly resistant to corrosion and lifting

3.1.4 Product system

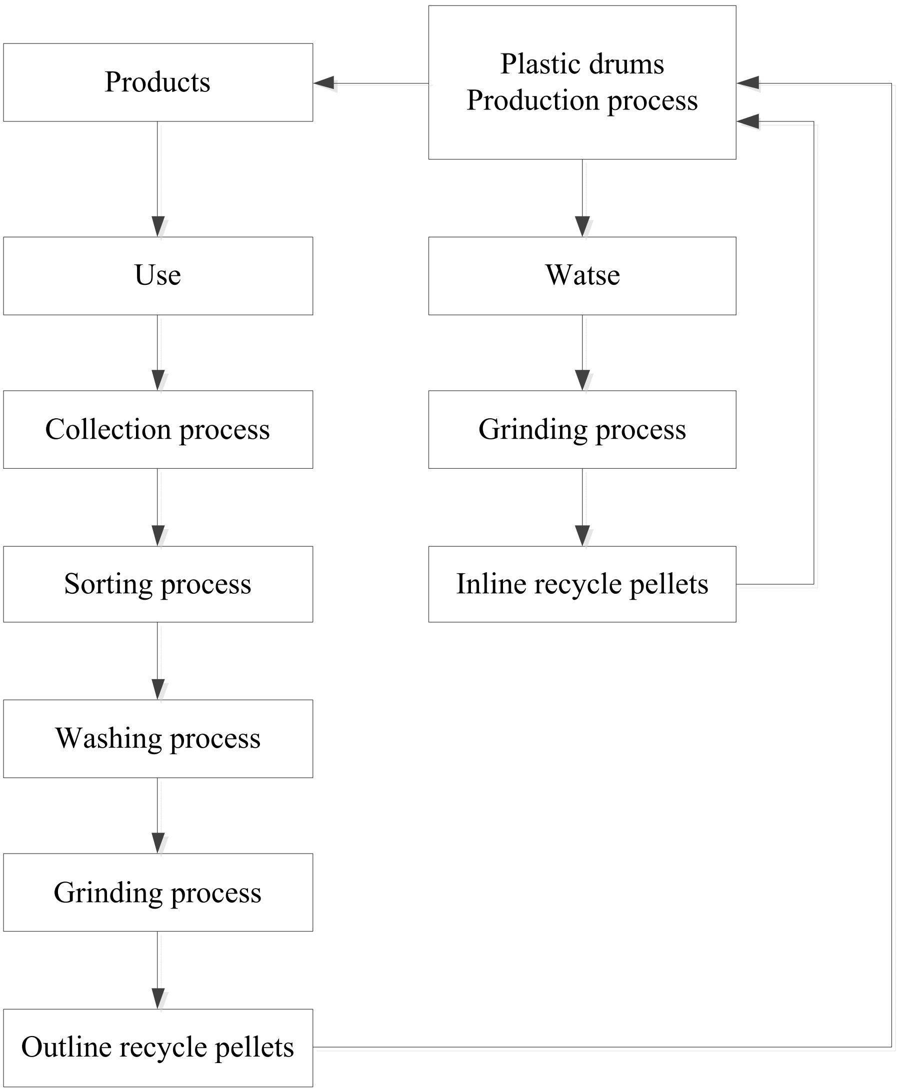

Figure 3.1 System boundary of plastic drum production

3.2 Data collection

3.2.1 Life cycle inventory of raw material

3.2.1.1 Upstream process

The study of life cycle from upstream process comprised of quantity of energy, resource and pollution caused by production process of substrate used in production including obtainment of pure plastic pellets, and secondary color obtainment studied from secondary data and obtainment of recycled plastic pellets studied from primary data. The data was accumulated at the company. The value of energy, resource and pollution releasing from energy usage in transporting each type of core materials were studied from primary data.

3.2.1.2 Raw material production process

1) High-density polyethylene (HDPE) is new plastic obtained from petrochemical production process by studying data from energy and resource consumption as well as pollution caused by production process. It includes the obtainment of raw materials used to produce plastics, plastic pellet production process and disposal throughout useful life of products. Data were accumulated from plastic pellet manufactures or from Thai National Life Cycle Inventory Database.

2) Primary-recycled plastic pellets are wastes from inline recycle process called as plastic sheet. They will be processed as scraps and used in further production process. Value of Energy and resource consumption in plastic sheet processing will be included as energy and resource consumption of products to evaluate life cycle of plastic production.

3) Secondary-recycled plastic pellets are produced from plastic sheets in outline recycle. In this case, plastic drums that cannot be reused will be ground as plastic scraps before used in production process which comprises many procedures including gathering contaminated plastic drums, transporting, sorting, washing and grinding etc. Value of energy and resource consumption in each step will be used to evaluate life cycle of 1-kilogram secondary-recycled plastic pellet production.

4) Dyestuff; the usage of fuel, resource and pollution caused by color production to mix in plastic were studied by analyzing secondary data from both domestic and international researches.

3.2.1.3 Transportation of raw material

Studying data of raw material transportation in production process including transportation of new plastic pellet, transportation of secondary color and recycled plastic pellets. Data was accumulated in 3 relevant terms such as type of truck, quantity of transportation and distance. After that, the value would be used to evaluate environmental impact of products.

3.2.2 Main production process

This part illustrates studying about using energy, raw materials and releasing pollutions in 2 formulas of 20-liter HDPE drum production.

Production process of formula 1: data about energy and resource consumption in production process along with resources and energy used in grinding process of plastic sheets as wastes for recycling are accumulated to evaluate environmental impact of plastic drum formula 1 (as shown in figure 3.2).

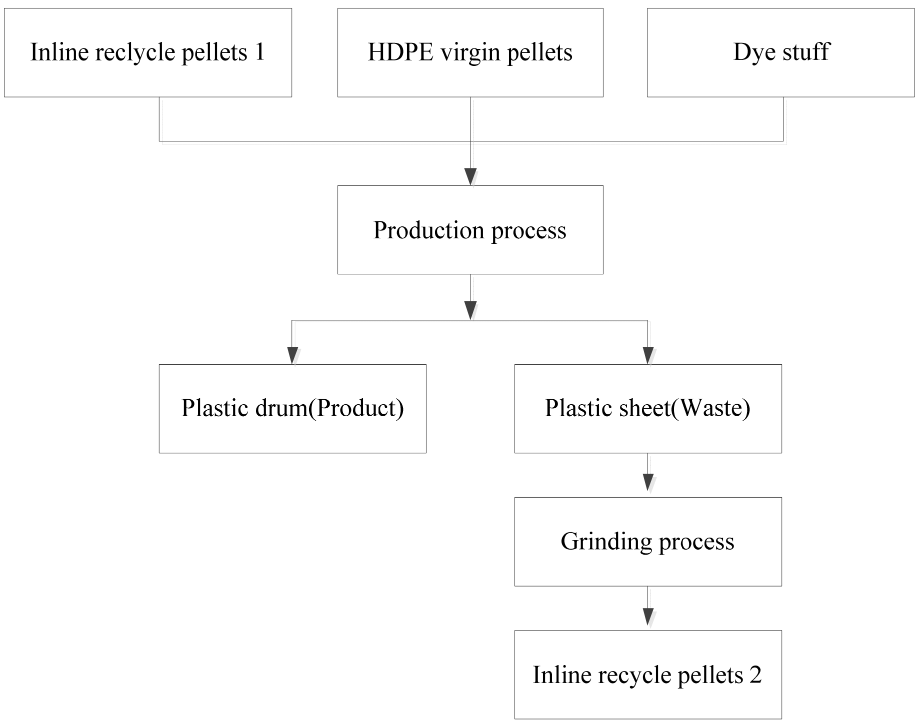

Figure 3.2 System boundary of plastic drum production formula 1

Production process of formula 2: data about resource and energy consumption in production process along with resources and energy used in grinding process of plastic as wastes for recycling are accumulated to evaluate environmental impact of plastic drum formula 2 (as shown in figure 3.3).

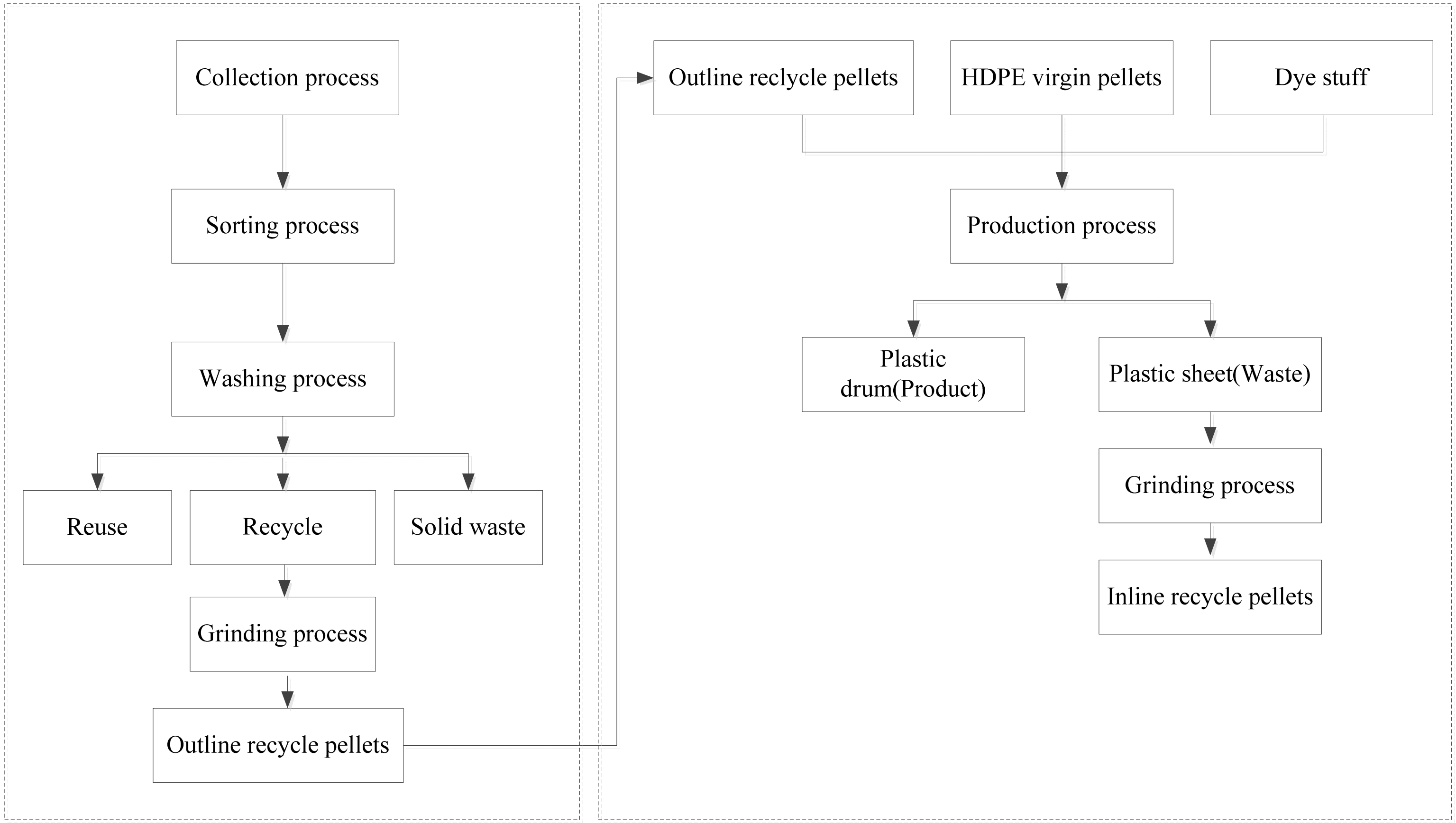

Figure 3.3 System boundary of plastic drum production Formula 2

3.2.2.1 Primary data

It was obtained from gathering data of plastic drum product in 3 formats including the usage of resource and energy and waste caused by each production format with mass balance and allocation by weight.

3.2.2.2 Secondary data

Potential values of environmental impact (Characterization Factor) and comparison of capability to originate environmental impact (Normalization factor) in midpoint and endpoint level needs the data of evaluation according to ReciPe 2008.

3.2.3 Product distribution and transportation

As this study was to evaluate life cycle of products in manner of business to business (B2 B), it was evaluated from process of raw material obtainment to production process. Therefore, data of product transportation and distribution was not considered.

3.2.4 Usage

As this study was to evaluate life cycle in format of business to business (B2 B), it was evaluated from process of raw material obtainment to production process and thus, data of plastic drum usage was not considered.

3.2.5 After usage (Disposal)

As this study was to evaluate life cycle in format of business to business (B2 B), it was evaluated from the process of raw material obtainment to production process only and thus, data of product residue disposal after usage was not considered.

3.3 Data analysis

3.3.1 Life cycle assessment

In this study, life cycle of HDPE drums in 3 types was assessed in accordance with the manual of product life cycle assessment of Thailand Environment

Institute Foundation 2004. It was assessing midpoint impacts in 3 terms including impact on global warming, impact on acidity and impact causing eutrophication and endpoint impacts in 3 terms including impact on health, resources and ecosystem. The assessment included equivalency factor according to the approaches of ReCiPe 2008 to calculate potential values that affected environment in each term with methods as below equation.

$$EP_j = \sum Q_i \times EF_{ij}$$

Where EPi is environmental impact potential of impact(j) (Kg substance equivalent)

Qi is quantity of substance of substance(i) emission to environmental(Kg substance i)

EFij is equivalent factor of substance(i) to cause environmental impact(j)(Kg substance i / Kg substance j)

3.3.2 Sensitivity analysis

Quality analysis of data related to data sensitivity analysis by changing production factors to evaluate tendency of changing impacts.

- The type of material used.
- The type of fuel used in the manufacturing process.
- The type of fuel used in the transportation process.
- Distance shipping.
- Mixing ratio
- Assessment form the calculation is as follows:

Deviation $= (A - B)$

Percentage changes $= \left(\frac{A-B}{A}\right) \times 100$

The sensitivity $= \left|\left(\frac{A-B}{A}\right) \times 100\right|$

Where A is the impact caused by normal processes.

B is the impact of changes in various factors in the production process.

3.4 Life cycle interpretation

The derived result from assessment of life cycle of each type of plastic drums was analyzed and indicated the factors resulting in environmental impact and approaches of development and improvement so as to mitigate environmental impact. The data were compared as guideline to suggest alternatives for the entrepreneurs in production as follows;

3.4.1 Comparison of eco-efficiency of plastic drum production process

Data about cost of plastic production in each formula are accumulated to evaluate eco-efficiency such as raw material cost, transport cost, production and labor cost etc. after that, the aggregate of each cost type will be calculated for production cost of each production formula and the result is compared with environmental impact value to evaluate eco-efficiency as shown in below equation;

$$\text{Eco-Efficiency} = \frac{\text{Product or service value}}{\text{Environmental influence}}$$

Where Eco-Efficiency is Eco-efficiency of product consider
Product or service value is cost of production consider
Environmental influence is Environmental impact of midpoint level

To enhance eco-efficiency can be done in various approaches such as improving production process or using environmentally-friendly raw materials to diminish environmental impact with proper costs. Eco-efficiency measurement will be conducted by comparing it in form of factors which is eco-efficiency comparison before and after process improvement as below equation;

$$\text{Factor X} = \frac{\text{EE of evaluated product}}{\text{EE of the reference product}}$$

Where Factor X = different eco-efficiency
EE of evaluated product = Eco-efficiency after improvement
EE of reference product = Eco-efficiency before improvement

The factor obtained from calculation may vary such as 0.5, 1.0, 1.2, 3.0, 5.0 etc. depending on ability of development and improvement of that organization. Therefore, this factor is normally referred to as “Factor X where X represents any number.

3.4.2 Pollution prevention cost analysis

Pollution prevention cost was evaluated by calculating midpoint pollution value in each term of plastic drum production with pollution prevention cost according to the methods of Vogtlander (2001). It was to assess the cost of general pollution creation in each format of plastic drum production as alternatives for the entrepreneurs in considering proper production process by calculating pollution prevention according to the equation.

Pollution prevention cost = ∑(Environmental impact X Marginal prevention cost)

Where Pollution prevention cost is pollution prevention cost of consider

Environmental impact (midpoint) is environmental impact of consider

Marginal prevention cost is marginal prevention cost of consider

3.4.3 Comparison study

The data from the study in the form of environmental impact from the stage of the product life cycle assessment of each plastic drums compared with the research that has been studied before. This compares to the results of the study and data analysis.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life cycle inventory of high-density polyethylene plastic drum

4.1.1 Life cycle inventory of raw materials

4.1.1.1 LCI of general virgin HDPE plastic pellets

The life cycle inventory of virgin High-density polyethylene plastic pellet in terms of environmental usage, energy and wastes caused by the process were referred from national life cycle inventory from National Metal and Materials Technology Center (MTEC) (appendix A).

4.1.1.2 LCI of primary recycles pellets (Inline recycle)

Primary recycled plastic pellets for this research were virgin pellets obtained from plastic scraps in the plastic drum production process. In this process, it was necessary to feed adequate materials to molding thus resulting in the surplus amount of plastic scraps. According to the plastic production data collected during July 2014- June 2015, it was found that among plastic scraps of 59.36 tons accounting as 24% of all materials in production process, 30.87 ton was white plastic scraps and 28.49 ton was clear plastic as shown in table 4.1(Appendix D-5).

Plastics obtained from the production process were ground as primary recycled plastic pellets with plastic grinding machine and they were mixed with materials for next production. To produce primary recycled white plastic pellets for 30.87 ton and clear plastic pellets for 28.49 ton, the processes required electric power for grinding of 855.88 kilowatt per hour or grinding ratio was 0.0144 kilowatt per hour per kilogram as shown in figure 4.1.

Table 4.1 Life cycle inventory data of inline recycle pellets of crushing process

Product and co-product	Amount	Unit	%Allocation
Product			
Inline recycle pellets (white)	30.87	ton	52.00%
Inline recycle pellets (clear)	28.49	ton	48.00%
Input			
Raw material and Utility	Amount	Unit	Remark
Plastic sheet (white)	30.87	ton	
Plastic sheet (clear)	28.49	ton	
Electricity	855.88	kWh	

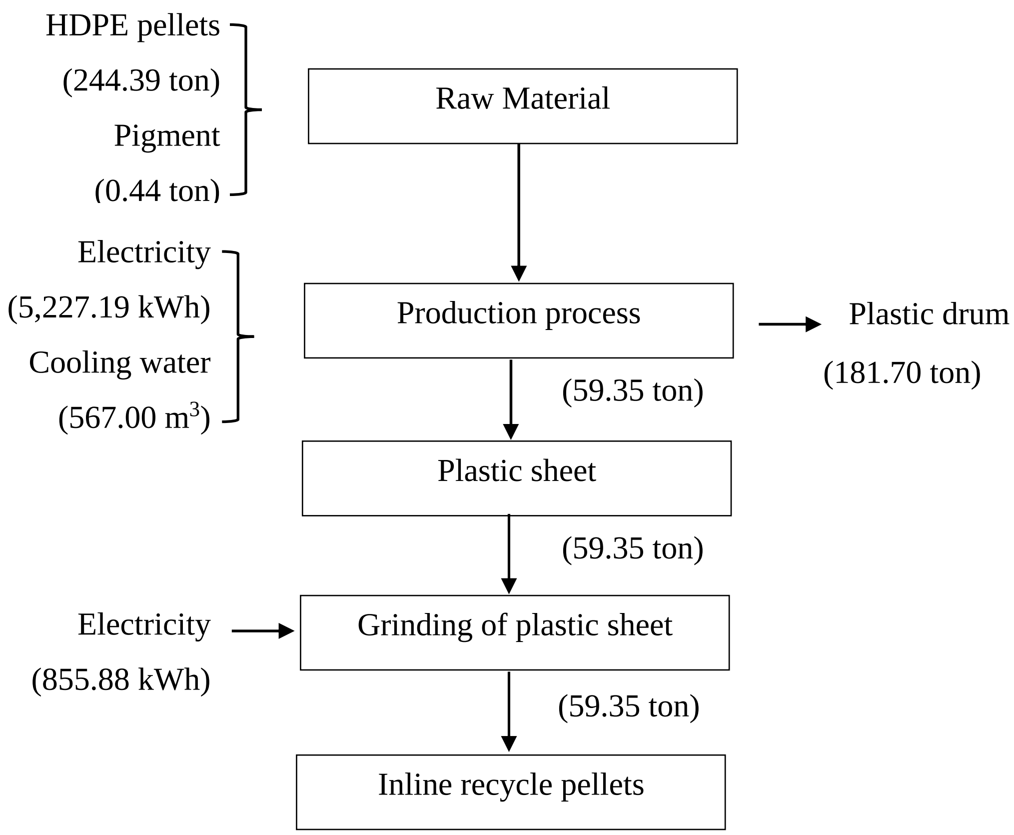

Figure 4.1 LCI of inline recycles pellets

4.1.1.3 LCI of secondary recycled pellets (outline recycle)

1) Collection of contaminated plastic drums

The information on contaminated plastic drums was obtained from the record forms for contaminated plastic drum collection from customers of the company that studied about gathering contaminated plastic drums to the cleaning unit after delivery to the customers. Contaminated plastic drums would be collected from dealers throughout the nation for 25 stations (Appendix B) by calculating distance from contaminated plastic drum collection unit to cleaning unit from website of Department of Highways. The collection was conducted with 2 types of trucks including 4-wheel truck and 6-wheel truck. It was found that the quantity of Returned contaminated plastic drums was 111.46 Ton, of which 44.58 Ton was ground to be plastic pellets and 66.88 Ton of plastic drums was reused as shown in table 4.2 (Appendix D-3).

Table 4.2 Life cycle inventory data for collection and transportation process

Product			
Product and Co-product	Amount	Unit	%Allocation
Plastic drum (recycle)	44.58	ton	40.00%
Plastic drum (other)	66.88	ton	60.00%
Input			
Raw materials and Utilities	Amount	Unit	Remark
Postconsumer plastic drum	111.46	ton	
NGV for pick up type, 4 wheels	19,350	kg	
NGV for lorry transport, 6 wheels	2,880	kg	

2) Contaminated plastic drum cleaning

After transporting contaminated plastic drums back to the cleaning unit, the undertaker would classify drums according to quality of each product type such as acidity, neutrality and alkalinity and as cleaning process of each type took long times, some drums have not been cleaned immediately. According to the data of transporting contaminated plastic drum back to cleaning unit, it was found that for 111.46-Ton contaminated plastic drums were sent to cleaning process, only

91.55 Ton was completely cleaned and the remainders of 19.91 Ton was pending for further cleaning.

According to the information of 91.55 Ton of contaminated plastic drums that were cleaned, it was found that it consumed electricity for 786.52 Kilowatt per hour and 1,479 cubic meter water resulting wastewater for 1,479 cubic meter and hazardous solid from label scraps, film covers and plastic drum cover for 2.35 Ton to be further disposed in form of hazardous solid.

The cleaned plastic drums could be divided into 2 types including plastic drum for reuse of 53.95 Ton and plastic drum to be ground as recycled plastic pellets used in production process for 35.24 Ton accounting for 39.5% of all plastic drum weight imported to cleaning process.

Plastic drums that could not be reused would be sent in cleaning process and dried before cut and ground as secondarily recycled plastic pellets for further production. According to the data of grinding secondarily recycled plastic pellets, it was found that producing 35.24 Ton of plastic pellets used electricity for grinding of 78.31 Kilowatt per hour. After that recycled plastic pellets were contained in HD plastic bag obtained from used pure plastic pellet containing bag for further usage as show in table 4.3(Appendix D-4)

Table 4.3 Life cycle inventory data of washing process

Product and Co-product	Product Amount	Unit	%Allocation
Plastic drum (Recycle)	35.24	ton	39.5%
Plastic drum (Other)	53.95	ton	60.5%
Postconsumer plastic drum	91.55	ton	1.1188 kg./unit
Washing agent	214.82	kg	
Electricity	786.52	kWh	
Tap water	1,479.00	m^3	

Table 4.3 Life cycle inventory data of washing process (cont.)

Product and Co-product	Amount	Unit	%Allocation
Output			
Category	Amount	Unit	Remark
Waste water	1,479.00	m^3	
BOD	75.72	kg	
COD	126.19	kg	
Suspend solids	41.68	kg	

Table 4.4 Life cycle inventory data of crushing process

Product and Co-product	Amount	Unit	%Allocation
Outline recycle pellets	35.24	ton	100%
Input			
Raw material and Utilities	Amount	Unit	Remark
Plastic drum (Recycle)	35.24	ton	1.10 kg./unit
Plastic bag	14.00	kg	0.35 kg./unit
Electricity	78.31	kWh	

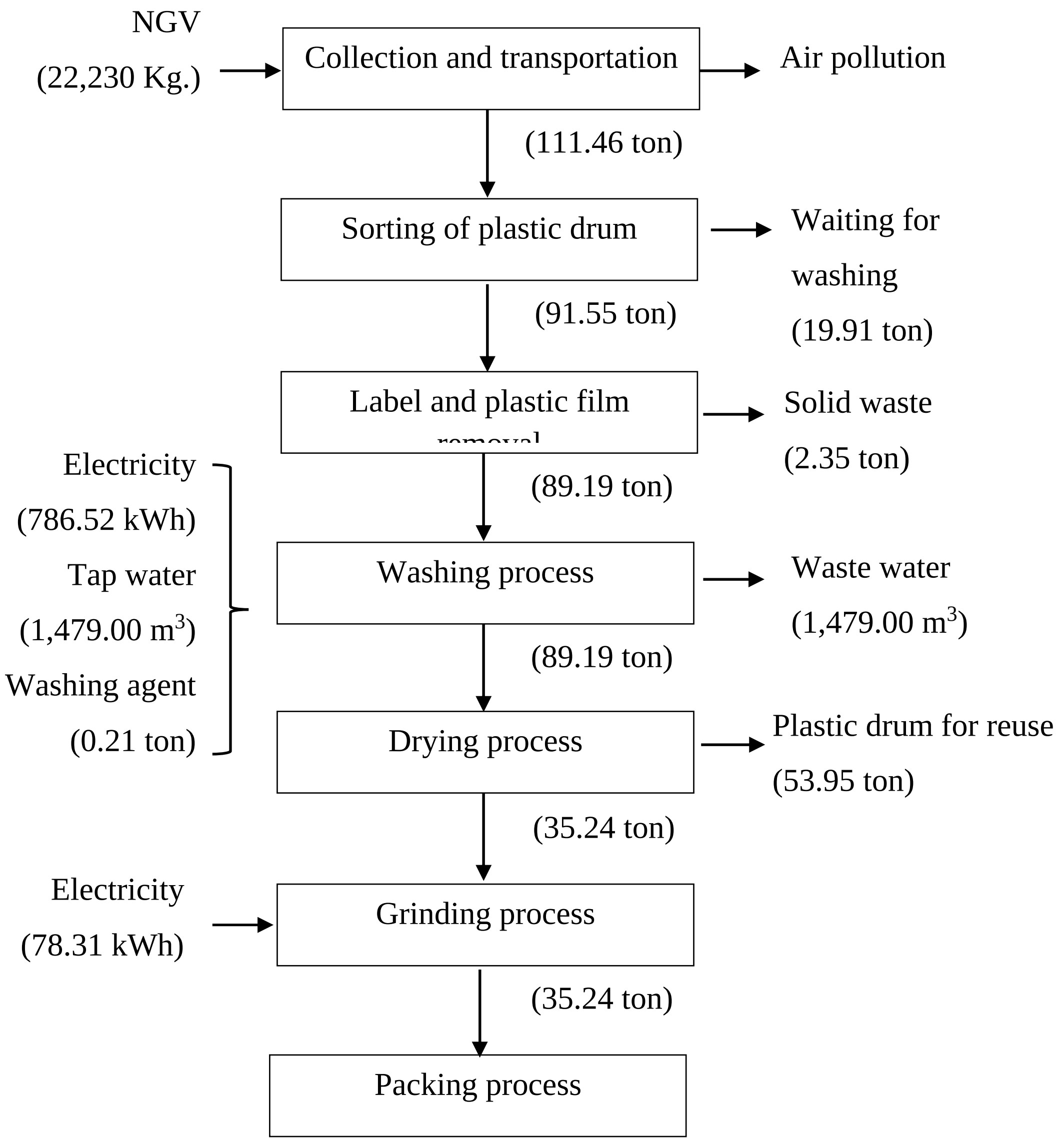

Figure 4.2 LCI of outline recycled pellets

4.1.1.4 LCI of dyestuff

Life cycle inventory of dyestuff was referred from data of studying the evaluation of powdered color cycle of Kritsakorn (2006) that evaluated the life cycle of powdered color from resources usage, energy and waste from production process including disposal as shown in Appendix E

4.1.1.5 Transportation

The transportation of virgin pellets and dyestuff for use in manufacturing processes, calculating distance transport from suppliers to the manufacturer at Phetchaburi province from the website of the Department of Highways, except secondary recycle pellets measure the distance from the washing station to production area by measuring tape. The primary recycle pellets cannot be transported due to production area as show in table 4.5

Table 4.5 Transportation data of raw material

Raw material	Distance	Unit	Vehicles types
HDPE virgin pellets	119.63	km.	Lorry transport, 6 wheels
Primary HDPE recycle pellets	0.00	km	-
Secondary HDPE recycle pellets	0.80	km	Forklift
Pigment	100.10	km	Pick up type, 4 wheels

4.1.2 High-density polyethylene plastic drum production

The process for producing both formulas of high-density polyethylene plastic drum was conducted with blow molding extrusion method. Data of producing plastic drums were accumulated from a plastic drum manufacturer in Phetchaburi for 12 months (July 2014-June 2015). It was the analysis of quantity of entry substances and outcome from production process of plastic drum in terms of resource consumption energy and waste caused by 2 formulas of production process. It was found that plastic pellets of 244.39 ton were used in production of both white and clear plastic drum including 0.44-ton color for only white drum production. Electricity of 5,227.19 Kilowatt/hour was used for whole production including 567-cubic meter cooling water for production process. This would produce white plastic drum for 96.46 Tons or 87,689 drums (weight 1.10 kilogram/drum) and clear plastic drum for 85.25 Ton or 80,931 drums. Besides, white plastic scraps of 30.87 Ton and clear plastic scraps of 28.49 ton or 32% of all used materials were obtained from production process (as shown in table 4.6).

Table 4.6 Life cycle inventory data for production process of plastic drum

Product			
Product and co-products	Amount	Unit	%Allocation
Plastic drum(white)	96.46	ton	39.40%
Plastic drum(clear)	85.25	ton	36.36%
Plastic sheet(white)	30.87	ton	12.61%
Plastic sheet(clear)	28.49	ton	11.64%
Input			
Raw material and utilities	Amount	Unit	Remark
Plastic pellets	244.39	ton	
Pigment	0.44	ton	
Electricity	5,227.19	kWh	
Cooling water	567.00	m^3	
Output			
Category	Amount	Unit	Remark
Plastic bag of plastic pellets	2,443.90	kg	Reuse
Plastic bag of pigment	14.08	kg	Disposal

4.2 Life cycle assessment of High-density polyethylene plastic

4.2.1 Life cycle inventory of plastic drum production process

From the production process of 2 types of high-density polyethylene plastic drums of a plastic drum manufacturer in Phetchaburi, the quantity of input and output substances from production process in terms of resource and energy consumption and waste caused by the production process of 2 types during July 2014 – June 2015 (12 months) were analyzed. It was calculated equally to the quantity of producing a plastic drum. It was found that 1.5990 kilogram plastic pellets, 0.0033 kilogram color, 0.0329 kilowatt electricity and 0.0128 cubic meter cooling water were used in production process to derive a plastic drum with total weight of 1.1056 kilogram and there were average plastic scraps from production process of 0.4967 kilograms accounting for 31%. It would be ground and used as mixture in next plastic drum production as shown in table 4.7

Table 4.7 Life cycle inventory data for production of plastic drum 2 formulas

Process	Raw material	Unit	Production process	
			Formula 1	Formula 2
Input	HDPE virgin pellets	kg	1.0523	1.0523
	Primary recycle pellets	kg	0.5467	0.0000
	Secondary recycle pellets	kg	0.0000	0.5467
	Pigment	kg	0.0033	
	Electricity	kWh	0.0329	
	Cooling water	m^3	0.0128	
Output	Plastic drum	kg	1.1056	
	Plastic sheet	kg	0.4967	
	Packaging (virgin pellets)	kg	0.0160	
	Packaging (pigment)	kg	0.0001	

4.2.2 Environmental impact assessment of polyethylene plastic drum production process

To assess environmental impact of High-density polyethylene plastic drum, the ReCiPe 2008 methods in SimaPro 8.1 was used for evaluating midpoint to endpoint and evaluating eco-efficiency and values of pollution prevention of each production type by comparing environmental impact from 1-unit product.

4.2.2.1 Midpoint environmental impact assessment

Results of the midpoint environmental impact assessment of both methods of the HDPE plastic drum production process showed that the Formula 2 had a less midpoint impact than the Formula 1, with total impact values of 5.58E-03 and 6.28E-03, respectively. The majority of the impact was due to virgin plastic pellets. Also, the Formula 1 made use of plastic flake remains from the production process, which a hidden impact value, thus causing the total impact value of the Formula 1 to be higher.

In consideration of the overall impact, both production formulas gave impact in the same direction for two key points: fossil depletion and climate change, which made up 55% and 16% of the total impact, respectively. This was due to the fact that most materials used in the production process were products that had been synthesized from crude oil, an important natural resource. Fuel combustion that occurred in the transportation process was an important factor that contributed to climate change, giving a high impact

After considering each process step of the midpoint environmental impact, it was found that the Formula 2 had higher impact significant than the Formula 1 in two aspects: Terrestrial ecotoxicity and marine ecotoxicity. Their impact values differed up to 1119% and 988%, respectively, when compared to the Formula 1. In the production process, recycled plastic pellets in the Formula 2 had been cleaned by water and cleaning chemicals before being crushed, compared to the Formula 1 which utilized only electricity in the crushing process. Therefore, the impact values were higher for the Formula 2 in the ecotoxicity aspects. However, because the severity of the two impacts were considerably low, they contributed little (0.05% and 0.38%, respectively) to the total impact.

The evaluation of midpoint life cycle impact in 18 terms according to method of ReCiPe2008 for 2 formula of chemical plastic drum production was found that production in Formula 1 and 2 consisted of midpoint impact equal to 6.28E-03 and 5.58E-03 respectively as show in table 4.8. The impact of causing Fossil depletion and climate change around to 55% and 16% respectively as shown in figure 4.3

Table 4.8 Environmental impact assessment of midpoint level

Impact category	Unit	Formula 1	Formula 2	Diff.	%Diff
CC	kg CO_2 eq	1.10E+01	1.07E+01	3.35E-01	3.05
OD	kg CFC-11 eq	5.02E-09	5.10E-09	-7.61E-11	-1.52
TA	kg SO_2 eq	1.83E-02	1.75E-02	8.08E-04	4.42
FE	kg P eq	2.02E-04	2.02E-04	-7.63E-08	-0.04
ME	kg N eq	3.95E-04	6.24E-04	-2.29E-04	-57.88
HT	kg 1,4-DB eq	1.42E-03	2.41E-03	-9.93E-04	-69.92
POF	kg NMVOC	9.25E-03	1.66E-02	-7.39E-03	-79.85
PMF	kg PM10 eq	5.12E-03	5.59E-03	-4.70E-04	-9.17
TET	kg 1,4-DB eq	3.79E-06	4.62E-05	-4.24E-05	-1119.75
FET	kg 1,4-DB eq	2.99E-05	3.12E-05	-1.28E-06	-4.28
MET	kg 1,4-DB eq	3.44E-05	3.74E-04	-3.40E-04	-988.05
IR	kBq U235 eq	6.06E-03	6.15E-03	-8.94E-05	-1.47
ALO	m2a	7.68E-06	9.70E-06	-2.02E-06	-26.30
ULO	m2a	1.60E-06	2.02E-06	-4.20E-07	-26.28
NLT	m^2	2.28E-08	2.89E-08	-6.06E-09	-26.59
WD	m^3	1.54E-02	1.43E-02	1.14E-03	7.42
MRD	kg Fe eq	2.80E-03	2.58E-03	2.16E-04	7.71
FD	kg oil eq	5.77E+00	4.42E+00	1.35E+00	23.45
Normalization		6.28E-03	5.58E-03	7.00E-04	11.15

Table 4.9 Environmental impact assessment of midpoint level with normalization

Impact category	Formula-1		Formula-2	
	midpoint	Percentage	midpoint	Percentage
CC	9.85E-04	15.69	9.51E-04	17.06
OD	2.28E-07	0.00	2.31E-07	0.00
TA	5.34E-04	8.50	5.09E-04	9.13
FE	4.87E-04	7.76	4.87E-04	8.73
ME	3.90E-05	0.62	6.16E-05	1.10
HT	2.26E-06	0.04	3.84E-06	0.07
POF	1.63E-04	2.59	2.93E-04	5.25
PMF	3.43E-04	5.47	3.75E-04	6.73
TET	4.58E-07	0.01	5.59E-06	0.10
FET	2.72E-06	0.04	2.83E-06	0.05
MET	3.95E-06	0.06	4.30E-05	0.77
IR	9.70E-07	0.02	9.84E-07	0.02
ALO	1.70E-09	0.00	2.14E-09	0.00
ULO	3.93E-09	0.00	4.97E-09	0.00
NLT	1.41E-07	0.00	1.79E-07	0.00
WD	0.00E+00	0.00	0.00E+00	0.00
MRD	3.91E-06	0.06	3.62E-06	0.06
FD	3.71E-03	59.12	2.84E-03	50.92
Total	6.28E-03	100.00	5.58E-03	100.00

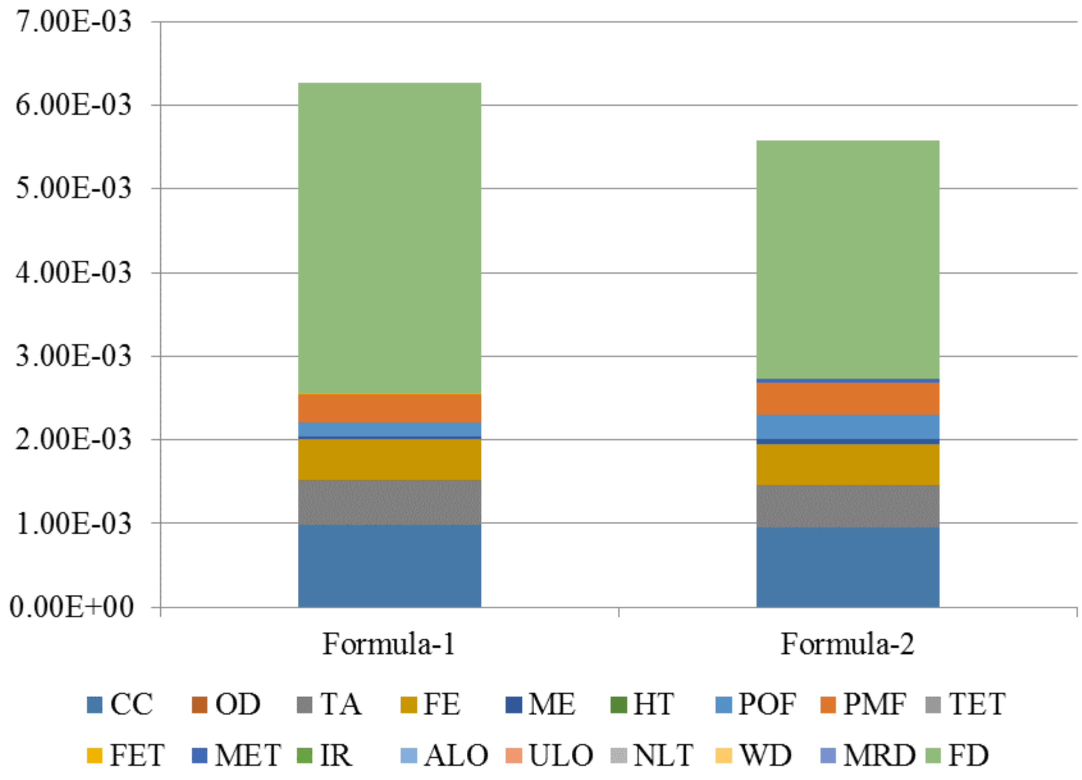

Figure 4.3 Environmental impact assessment of midpoint level normalization by ReCiPe 2008 method

Furthermore, most midpoint impact occurred in three process, raw material production, disposal and reuse attributing average to 78.26%, 11.02% and 10.32 of the total impact, respectively. Production of raw materials had higher impact significant because it is the core process especially virgin plastic pellets which are from petrochemical product to made high impact in the fossil depletion. In addition the reuse process of this study, plastic drums had been reused two more times, before being crushed into secondary recycled plastic pellets. The reused process had to many sub-process, such as transportation of contaminated plastic drums to the cleaning division, separation, and cleaning sub-step. These caused the impact value of the usage to be relatively high, especially in the transportation which was not as efficient as it should be, because the quantity per travel was only 5% loading of the total transportation weight. Manufacturer should try to improve in this regard; for example, by specifying a regional drum reception point and by crushing expired drums before transporting to the cleaning division in order to increase the transportation capacity, increase the transportation efficiency, and reduce impact to the environment.

Table 4.10 Environmental impact assessment of midpoint impact by process step

Process	Raw material	Midpoint potential : ReCiPe2008	
		Formula 1	Formula 2
Raw material	HDPE virgin pellets	3.32E-03	3.32E-03
	Primary recycle pellets	1.73E-03	0.00E+00
	Secondary recycle pellets	0.00E+00	9.25E-04
	Pigment	2.39E-07	2.39E-07
	Total	5.05E-03	4.24E-03
	Percentage	**80.44**	**76.09**
Production process	Electricity	7.67E-06	7.67E-06
	Tap water	1.31E-05	1.31E-05
	Total	2.08E-05	2.08E-05
	Percentage	**0.33**	**0.37**
Transportation	Transportation of plastic pellets	2.63E-06	2.63E-06
	Transportation of pigment	2.37E-08	2.37E-08
	Total	2.65E-06	2.65E-06
	Percentage	**0.04**	**0.05**
Reuse	Collection	2.12E-04	3.18E-04
	Washing	3.42E-04	3.42E-04
	Total	5.53E-04	6.59E-04
	Percentage	**8.82**	**11.83**
Disposal	Solid waste	6.51E-04	6.51E-04
	Percentage	**10.37**	**11.67**
Total process		**6.28E-03**	**5.58E-03**

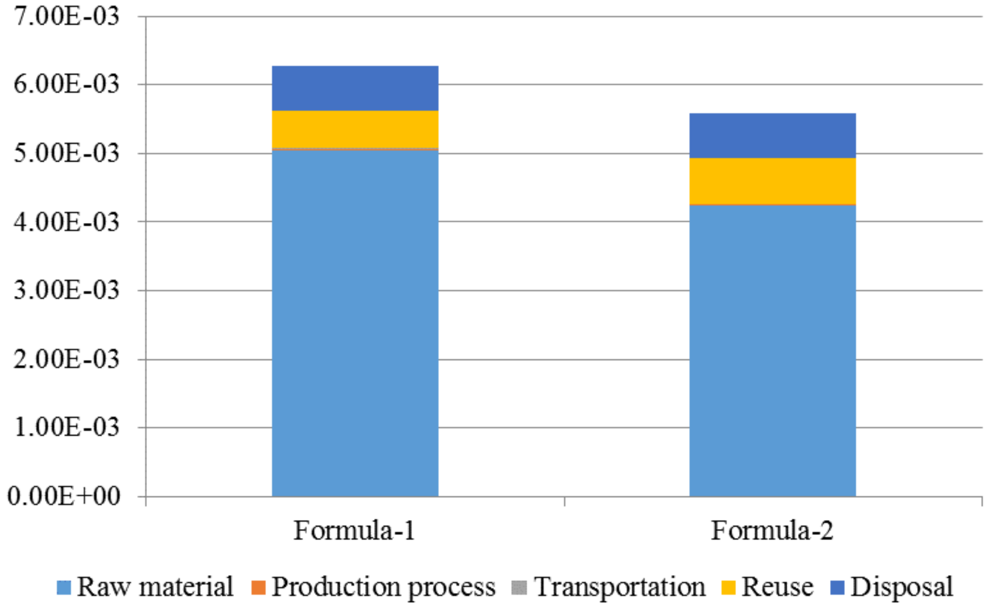

Figure 4.4 Environmental impact assessment of midpoint of production process by ReCiPe 2008 method

4.2.2.2 Endpoint Environmental Impact Assessment

The assessment of endpoint life cycle of chemical container production in form of single score was generally found that the impact from production process Formula 1 and 2 was equal 1.1453Pt and 0.9855Pt respectively (figure 4.5).

Results of the endpoint environmental impact assessment of both formulas of the plastic drum production process showed that the Formula 2 had less impact than the Formula 1 with regard to natural resource, health, and ecological impacts, attributing 23.46%, 3.42%, and 2.38%, respectively.

After consideration of the overall endpoint impact, it was found that both formulas of production impacted the environment in the same direction. They impacted natural resource usage for 51% and human health for 31%. The main material used in the production process was high-density polyethylene plastic pellets, which had been petro-chemical synthesized with crude oil as their substrate, an important natural resource; thus, lending to the natural resource usage impact. In addition, fuel resources were used in the transportation process, affecting climate change; thus, impacting human health.

Table 4.11 Environmental impact assessment of endpoint level w

Damage category	Unit	Endpoint potential : ReCiPe2008			
		Formula 1	Formula 2	Diff.	%Diff.
Human Health	DALY	1.68E-05	1.64E-05	4.00E-07	2.38
Ecosystems	species.yr	8.77E-08	8.47E-08	3.00E-09	3.42
Resources	$	9.55E-01	7.31E-01	2.24E-01	23.46

Table 4.12 Environmental impact assessment of endpoint level with single score

Damage category	Unit	Formula-1		Formula-2	
		endpoint	Percentage	endpoint	Percentage
Human Health	Pt	0.3325	29.03	0.3244	32.92
Ecosystems	Pt	0.1939	16.93	0.1873	19.01
Resources	Pt	0.6189	54.04	0.4738	48.07
Total	Pt	1.1453	100.00	0.9855	100.000

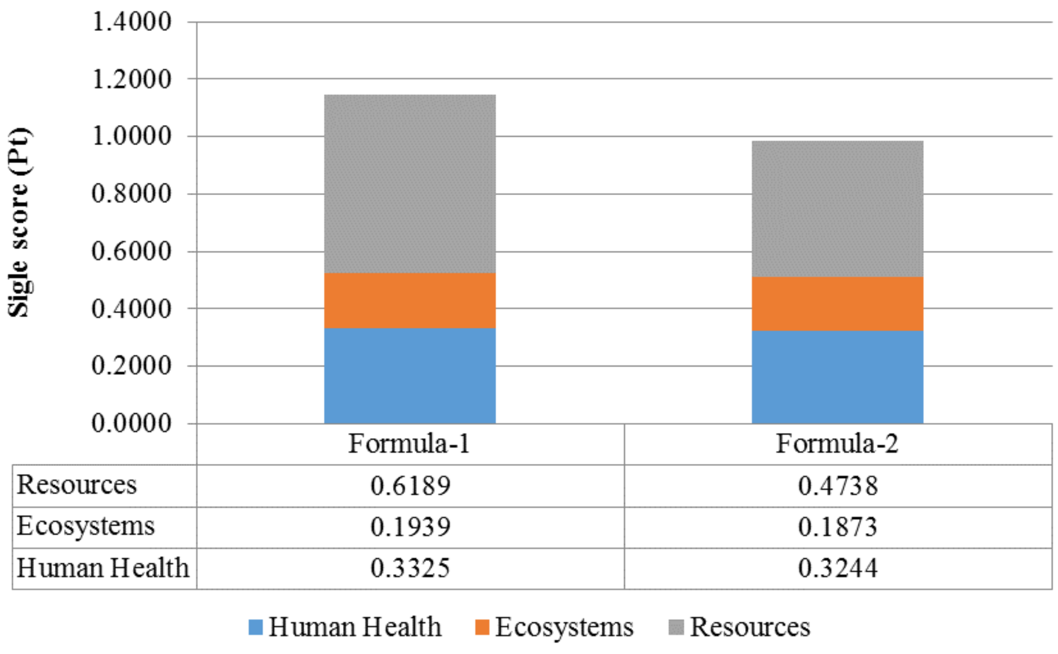

Figure 4.5 Environmental impact assessment of endpoint level of plastic drum

4.3 Sensitivity Analysis

Study results found that the Formula 2 of plastic drum production, which used virgin plastic pellets mixed with secondary recycled plastic pellets in the proportion 65:35, impacted the environment less than the Formula 1. However, the quantity of secondary recycled plastic pellets might not be adequate for the total demand of plastic pellets. Demand for plastic pellets in 2016 was approximately 244.39 tons, in which 85.54 tons were secondary recycled plastic pellets. Meanwhile, only 44.58 tons of recycled plastic pellets could be returned to the system or 74.3% of the total number of drums in the system. Also, only 18.24% could be mixed into the production process. The main factor was the lack of material supply or contaminated plastic drums. At present, the rate of contaminated plastic drum accumulation for production of secondary recycled plastic pellets was only 74.3% of the total number of plastic drums. Therefore, manufacturers with a good management system might be able to increase the proportion of secondary recycled plastic pellets up to 24.55%, which would reduce the environmental impact for 2.59%.

Table 4.13 Sensitivity analysis of percentage of collection change

%Collection	Recycle (ton)	Virgin (ton)	Total (ton)	Product (ton)	Scarp (ton)	%Eff. (%)
74.3	44.58	82.79	127.37	96.01	31.36	Reference
80.0	48.00	89.14	137.14	103.38	33.76	7.67
90.0	54.00	100.29	154.29	116.30	37.99	21.13
100.0	60.00	111.43	171.43	129.22	42.21	34.59

Table 4.14 Sensitivity analysis of ratio secondary recycle pellets mixing change

Sensitivity of Collection change		%Mixing	Secondary recycle pellets	
%Collection	Amount(Ton)	(%)	Total impact	%Change
74.3%	44.58	18.24	1.16E-02	Reference
80%	48.00	19.64	1.15E-02	0.86

Table 4.14 Sensitivity analysis of ratio secondary recycle pellets mixing change (cont.)

Sensitivity of Collection change		%Mixing	Secondary recycle pellets	
%Collection	Amount(Ton)	(%)	Total impact	%Change
90%	54.00	22.09	1.14E-02	1.72
100%	60.00	24.55	1.13E-02	2.59

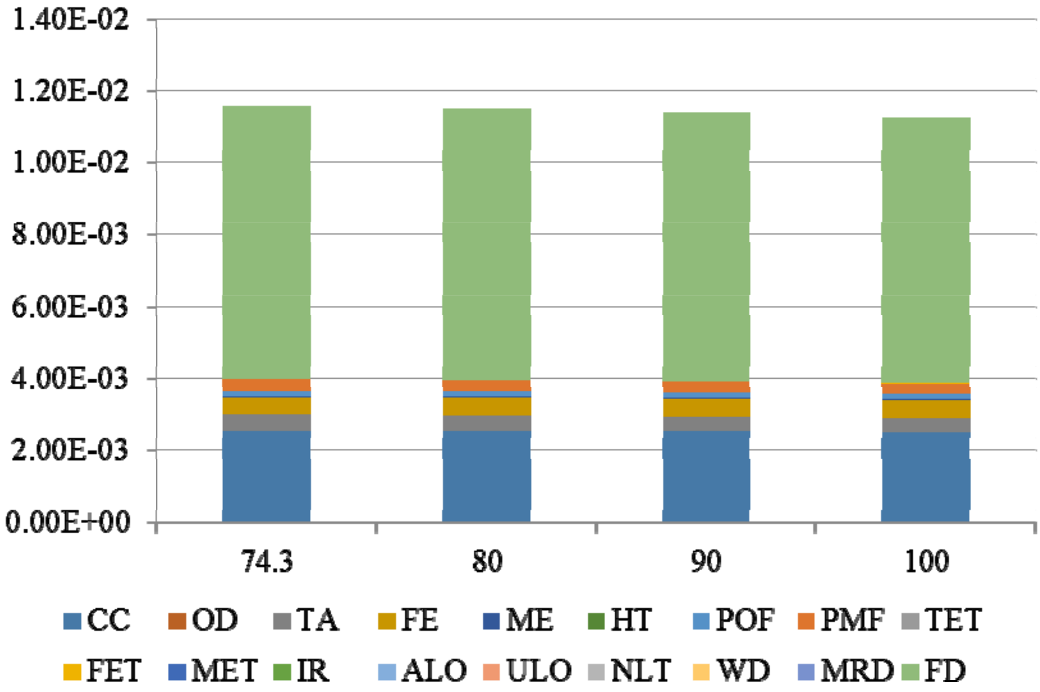

Figure 4.6 Influence of the ratio of HDPE virgin pellets and secondary recycle pellets

4.4 Interpretation and suggestion for improvement

4.4.1 Production cost of each plastic drum

Comparison of the costs of plastic drum production using Formula 1 and Formula 2 showed no difference in costs, because the raw materials and production process of both methods were similar, except for the crushing of plastic pellets that employed different types of crushing machines. The production cost of the Formula 1 was 86.59 Baht/unit, and the production cost of the second method was 86.57 Baht/unit. The major cost was virgin plastic pellets, making up 60% of the total cost, because they were the main raw material and priced relatively high (see table 4.15-4.17).

Table 4.15 Production cost of formula1

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
HDPE virgin pellets	Kg	49.12	1.0523	51.69
Pigment	Kg	125.00	0.0033	0.41
Primary recycle pellets	Kg	0.04	0.5467	0.02
Electricity/Unit	kWh	3.15	0.0316	0.10
Tap water/Unit	m^3	24.00	0.0128	0.31
Labor cost	Unit	21.08	1.000	21.08
Output				
Cost of disposal (Packaging of pigment)	Kg	3.8	0.8000	3.04
Cost of disposal (Packaging of pellets)	Kg	-3.8	0.5000	-1.90
Cost of disposal (Solid waste)	Kg	3.80	0.0287	0.11
Cost of grinding process	Kg	0.04	0.4967	0.02
Cost of reuse				
- Collection plastic drum	Kg	2.00	1.1000	2.20
- Washing plastic drum	Kg	4.00	1.1000	4.40
- Electricity of washing process	kWh	3.15	0.0350	0.11
- Tap water	m^3	24.00	0.0104	0.25
- Waste water treatment	m^3	4.75	1.0000	4.75
Plastic drum	Kg	-	1.1056	**86.59**

Table 4.16 Production cost of Sorting process 1 ton of primary recycle pellets

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
Plastic sheet	Kg	0.00	1,000	0.00
Electricity/Unit	kWh	3.15	14.42	45.42
Output				
Primary recycle pellets	Kg		1,000	45.42

Table 4.17 Production cost of formula 2

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
HDPE virgin pellets	Kg	49.12	1.0523	51.69
Pigment	Kg	125.00	0.0033	0.41
Secondary recycle pellets	Kg	0.007	0.5467	0.005
Electricity/Unit	kWh	3.15	0.0329	0.10
Tap water/Unit	m^3	24.00	0.0128	0.31
Labor cost	Unit	21.08	1.0000	21.08
Output				
Cost of disposal (Packaging of pigment)	Kg	3.80	0.8000	3.04
Cost of disposal (Packaging of pellets)	Kg	-3.80	0.5000	-1.90
Cost of disposal (Solid waste)	Kg	3.80	0.0287	0.11
Cost of grinding process	Kg	0.04	0.4967	0.02
Cost of reuse				
- Collection plastic drum	Kg	2.00	1.1000	2.20
- Washing plastic drum	Kg	4.00	1.1000	4.40
- Electricity of washing process	kWh	3.15	0.0350	0.11

Table 4.17 Production cost of formula 2 (cont.)

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Output				
- Tap water	m^3	24.00	0.0104	0.25
- Waste water treatment	m^3	4.75	1.0000	4.75
Plastic drum	Kg	-	1.1056	**86.57**

Table 4.18 Production cost of secondary recycle pellets

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
Plastic drum (Recycle)	Kg	0.00	1,000	0.00
Electricity/Unit	kWh	3.15	2.22	6.99
Output				
Secondary recycle pellets	Kg		1,000	6.99

4.4.2 Pollution preventive cost

The evaluation values of pollution preventive cost in plastic drum production process Formula-1 and 2 was equal to 2.24 and 1.94 euro/product unit respectively. Although the lowest values of pollution prevention causing global warming was 0.114 Euro/ unit, these 2 formulas of production process caused global warming higher than various terms due to the usage of materials with hydrocarbon compound that was main substances affecting global warming. Thus, the pollution preventive cost was higher than other terms up to 58% of total cost (shown in table 4.17).

Table 4.19 Pollution preventive cost of each plastic drum

Prevention of impact	Unit	Value Euro (€)	Formula 1		Formula 2	
			Impact	Value	Impact	Value
Global warming	kg CO_2-eq	0.114	1.08E+01	1.23	1.04E+01	1.19
Acidification	kg SO_2-eq	6.40	1.94E-02	0.12	1.89E-02	0.12
Eutrophication	kg PO_4^{3-}	3.05	4.82E-02	0.15	3.32E-02	0.10
Summer smog	kg VOC-eq	12.30	7.55E-04	0.01	3.14E-03	0.04
Winter smog	kg fine dust	50.00	1.45E-02	0.73	9.86E-03	0.49
Heavy metals	kg ZN-eq	680.00	4.20E-07	0.00	6.71E-07	0.00
Carcinogenics	kg PAH-eq	12.30	1.34E-08	0.00	1.70E-08	0.00
Total				**2.24**		**1.94**

4.4.3 Improvement and suggestion

4.4.3.1 Adjustment of plastic scrap proportion in process

Currently, entrepreneurs set up plastic drum production machine by using adequate raw materials to obtain quality plastic drums with least damages. The previous test results were found that plastic drums had high quality meeting required standards. However, there were high plastic scraps in production process up to 31% causing low production effectiveness.

Nevertheless, the research study of Soonthongchot (2010) on production process for polyolefin products was found that blow molding process contained waste rate for only 4.86% and product quality passed inspection standards. Thus, entrepreneurs may consider setting up the machine to diminish plastic scraps leading to lower production cost due to increasing products from the same amount of raw materials and to reduce energy used for grinding plastics. According to the experiment, the proportion of plastic scraps in production process was decreased to only 12% and 6% from total raw materials and it was fund that eco-efficiency could be increased for 1.73 and 1.80 times of process reference, respectively.

Table 4.20 Adjustment of plastic scrap proportion in production process

Process	Unit	Amount/Year		
Raw material	Kg	1.6023	1.6023	1.6023
Products	Kg	1.1056	1.4100	1.5062
Waste	Kg	0.4967	0.1923	0.0961
%Loss	(%)	31.00	12.00	6.00
Productivity	(%)	0.00	18.57	26.65
Midpoint impact	Normalized	4.27E-03	3.24E-03	3.14E-03
Product weight	Kg	1.1056	1.4100	1.5062
Eco-Efficiency		259	449	465
Factor improvement	-	Reference	1.73	1.80

4.4.3.2 Defining Regional Drum Gathering Point

According to data about contaminated drum transport from 25 stations sent to washing unit, it was found that the average transport round was 2,651 rounds/ year or total distance was 468,479 kilometers (as shown in table 4.19). Most transport weight per round was less than 5% of acceptable gross weight which substantially affected environment. Nevertheless, if regional gathering points for contaminated drums are determined to reduce distances and increase transport weight per round, environmental impacts can be mitigated.

According to the design of gathering points for contaminated drums in 3 points including northern region (Nakhonsawan), Northeastern region (Nakhonratchasima) and Southern region (Suratthani), the transport distance was reduced for 131,318 kilometers per year (as show in table 4.20) or decreased for 28% of original distance. Furthermore, it could reduce environmental impacts caused by using secondary plastic pellets for 35%.

Table 4.21 The traditional methods to collection of plastic drum

Regions	Station	Travel/month	Distance (Km/month)
Northern region	4	91	63,618
Northeastern region	4	75	41,416
Southern region	6	149	102,813
Eastern region	1	75	17,200
Bangkok	8	1,938	223,075
Western region	1	11	1,217
Southern region (Upper)	1	312	19,138
Total	25	2,651	468,479
Total weight of plastic drum (Ton)			111.46
Total plastic drum (Unit)			99,624
Transportation cost (2 Bath/Unit)			199,248
Transportation cost (Bath/Km.)			2.35
Midpoint impact (Normalization)			1.68E-03
Eco-efficiency			1.40E+03

Table 4.22 The new approach methods to collection of plastic drum

Regions	Station	Travel	Distance	Collection point	Travel	Distance	destination	Total distance
		Travel/month	Km/month	Province	Travel/month	Km/month	Province	Km/month
Northern	3	78	33,857	Nakhonsawan	1	350	Phetchaburi	34,207
Northeastern	3	50	15,105	Nakhonratchasima	1	365	Phetchaburi	15,470
Southern	5	138	25,793	Suratthani	2	1060	Phetchaburi	26,853
Eastern	0	0	0	-	75	17,200	Phetchaburi	17,200
Bangkok	0	0	0	-	1,938	223,075	Phetchaburi	223,075
Western	0	0	0	-	11	1,217	Phetchaburi	1,217
Southern (Upper)	0	0	0	-	312	19,138	Phetchaburi	19,138
Total	11	266	74,755		2,340	262,406		**337,161**
Total plastic drum (Unit)								99,624
Transportation cost (2 Bath/Unit)								199,248
Transportation cost (Bath/Km.)								1.80
Midpoint impact (Normalization)								1.21E-03
Eco-Efficiency								1.49E+03
Factor improvement								1.06

4.4.4 Result of Eco-Efficiency of HDPE plastic Drums

According to the environmental impact assessment of 2 formulas of plastic drum production, the Formula 2 production in which virgin plastic pellets were used and mixed with secondary pellets could affect environment least. Moreover, when considering impacts in each procedure of production, the researcher found that the stage of raw material obtainment affected environment most accounted for 88% of entire impacts especially the impact as causes of fossil depletion. This was because most activities were relevant to using hydrocarbon substances.

Hence, to develop eco-efficiency, the researcher has determined management process improvement especially the procedure of raw material obtainment for ultimate efficiency by comparing with eco-efficiency of the formula 2 production as referenced database. The determination covered 2 terms including reduction of plastic flake proportion in production process and definition of regional gathering points to reduce rounds of transporting contaminated drums to mitigate environmental impacts.

According to the experiment about process optimization by using data in 2 terms, it could diminish environmental impacts and enhance eco-efficiency up to 1.40 times compared to referenced database. The improvement by adjustment of plastic scrap proportion in process could mitigate environmental impacts up to 88% compared to the referenced database as show in table 4.23-4.25.

Table 4.23 Database of plastic drum production formula 2 for improvement

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
HDPE virgin pellets	Kg	49.12	1.0523	51.69
Pigment	Kg	125.00	0.0033	0.41
Secondary recycle pellets	Kg	0.007	0.5467	0.005
Electricity/Unit	kWh	3.15	0.0329	0.10

Table 4.23 Database of plastic drum production formula 2 for improvement (cont.)

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
Tap water/Unit	m3	24.00	0.0128	0.31
Labor cost	Unit	21.08	1.0000	21.08
Output				
Cost of disposal (Packaging of pigment)	Kg	3.80	0.8000	3.04
Cost of disposal (Packaging of pellets)	Kg	-3.80	0.5000	-1.90
Cost of disposal (Solid waste)	Kg	3.80	0.0287	0.11
Cost of grinding process	Kg	0.04	0.4967	0.02
Cost of reuse				
- Collection plastic drum	Kg	2.00	1.1000	2.20
- Washing plastic drum	Kg	4.00	1.1000	4.40
- Electricity of washing process	kWh	3.15	0.0350	0.11
- Tap water	m3	24.00	0.0104	0.25
- Waste water treatment	m3	4.75	1.0000	4.75
Plastic drum	Kg	-	1.1056	86.57
Cost of product/Kg	Bath			78.30
Plastic drum weight (Kg)				1.1056
Fossil depletion (KgOil-eq)				4.42
Eco-efficiency (Bath/KgOil-eq)				0.25

Table 4.24 Plastic drum production after improvement

Raw material	Unit	Cost/Unit (Baht)	Amount (Unit)	Production (Baht)
Input				
HDPE virgin pellets	Kg	49.12	1.0523	51.69
Pigment	Kg	125.00	0.0033	0.41
Secondary recycle pellets	Kg	0.007	0.5467	0.005
Electricity/Unit	kWh	3.15	0.0329	0.10
Tap water/Unit	m^3	24.00	0.0128	0.31
Labor cost	Unit	21.08	1.0000	21.08
Output				
Cost of disposal (Packaging of pigment)	Kg	3.80	0.8000	3.04
Cost of disposal (Packaging of pellets)	Kg	-3.80	0.5000	-1.90
Cost of disposal (Solid waste)	Kg	3.80	0.0287	0.11
Cost of grinding process	Kg	0.04	0.4967	0.02
Cost of reuse				
- Collection plastic drum	Kg	2.00	1.1000	2.20
- Washing plastic drum	Kg	4.00	1.1000	4.40
- Electricity of washing process	kWh	3.15	0.0350	0.11
- Tap water	m^3	24.00	0.0104	0.25
- Waste water treatment	m^3	4.75	1.0000	4.75
Plastic drum	Kg	-	1.5062	86.57
Cost of product/Kg	Bath			57.48
Plastic drum weight(Kg)				1.1560
Fossil depletion (KgOil-eq)				3.34
Eco-efficiency (Bath/KgOil-eq)				0.35

Table 4.25 Eco-efficiency comparison of plastic drum between before and after improvement

Impact	Unit	Plastic drum production process Formala-3	
		Reference	Improvement
Product weight	Kg	1.1056	1.1562
Fossil depletion (FD)	KgOil-eq	4.42	3.34
Eco-efficiency	Kg/KgOil-eq	0.25	0.35
Factor X		1.40	

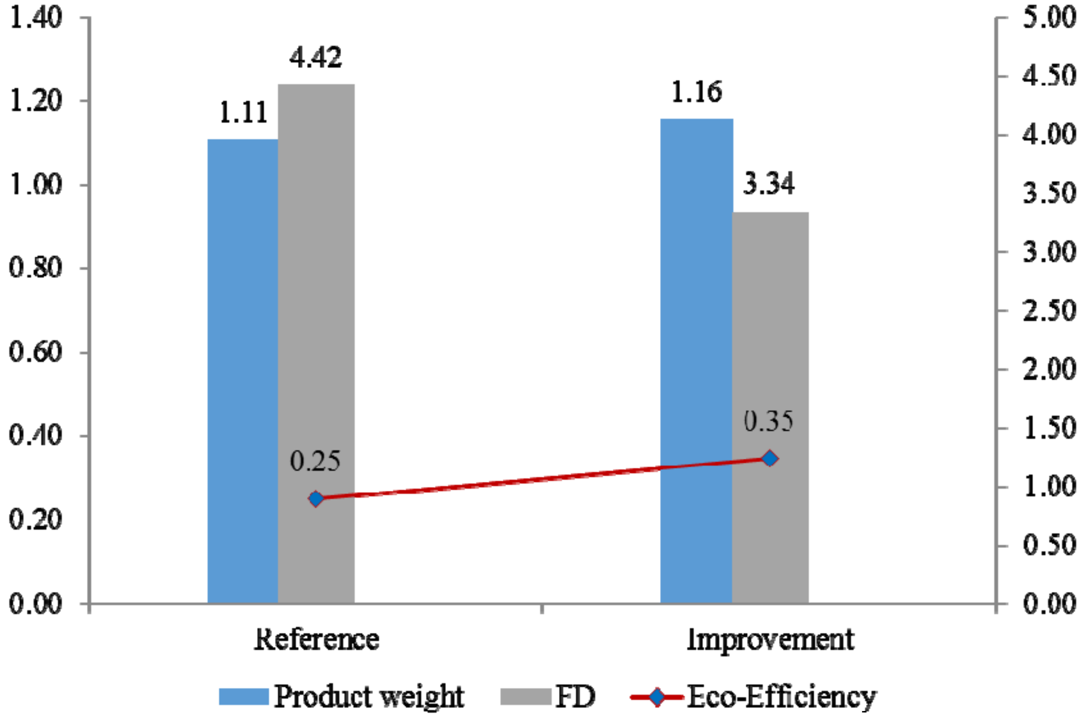

Figure 4.7 Eco-efficiency comparison of plastic drum between before and after improvement

4.4.5 Comparison Study

The result of studying greenhouse gas emission of plastic drums per 1 Kg product was found that value of greenhouse gas emission equaled 8.10 $KgCO_2$-eq/Kg which was similar to the study result of Soonthongchot (2010) who studied greenhouse gas emission of plastic containers in different production formats which equaled 7.49 KgCO_2-eq/Kg (as show in table 4.24). However such study result demonstrated that there were fewer wastes leading to lower environmental impacts.

Table 4.26 Comparison of GHG emission of plastic packaging

Process	Unit	Amount	
		Soonthongchot (2010)	This study
Raw material	ton	21.78	244.8
Product	ton	20.77	181.71
Waste	%	4.63	24.8
Electricity	kWh	147,245	5,227
GHG emission	Kg CO_2-eq		
Raw material	Kg CO_2-eq	4.12E+04	1.47E+06
Electricity	Kg CO_2-eq	1.22E+05	3.63E+03
Total	Kg CO_2-eq	1.63E+05	1.47E+06
Total/Kg of product	Kg CO_2-eq	7.49	8.10

CHAPTER V
CONCLUSIONS

5.1 Conclusions

The midpoint to endpoint life cycle impact assessment and eco-efficiency evaluation of two types of high density polyethylene drum produced from different types of HDPE pellets covered the raw materials production to production process and excluded the product use and disposal. The study was conducted by following ReCiPe2008 method using SimaPro 8.0 software. The results indicated that the type 2 production process which mixed virgin pellets with secondary recycled HDPE pellets caused less environmental impact than the type 1 production process for both midpoint and endpoint impacts. The total midpoint impact scores for type 2 and 1 processes were 5.58E-03 and 6.28E-03, respectively. The average impact of both production processes on fossil fuel depletion and climate change were the highest at 55% and 16% of the total impact, respectively. In addition, the endpoint impact of type 2 production process was also less than those of type 1. The total endpoint impact score of type 2 production process was 0.9855Pt meanwhile those of type 1 production process was 1.1453Pt. The average impact on depletion of natural resources and human health of both production processes were the highest at 51% and 31%, respectively. The stages of both HDPE tank production types which caused the highest impact were the product use and raw material production because the product use of this case study was considered twice reused so more resources were used leading more environmental impact. Moreover, the major impact from the production process was from the plastic pellets, the product of petrochemical process, which used crude oil, an important natural resources, as raw materials. Therefore, the obvious impacts were from the depletion of fossil fuel in the midpoint impact and natural resources in the endpoint impact.

The evaluation of eco-efficiency comparing to the cost of plastic tank production and the midpoint life cycle impact on global warming indicated that type 2 production process was also more valuable than type 1. The eco-efficiency value of type 2 and type 1 reduction process were 0.35 kg/kgOil-eq and 0.25 kg/ kgOil-eq, respectively.

The study showed that type 2 production process which used the virgin pallets mixed with secondary recycled HDPE pellets caused less midpoint and endpoint impacts and had higher eco-efficiency than type 1 production process. Therefore, type 2 production process was the most appropriate to be applied for the development of plastic tank production. However, the manufacturers currently collected the used plastic tanks for only 74.8% which might not be adequate. The manufacturers should have a better management for plastic tank collection, for instance, specify the tank collection area or crush expired tanks before transferring to increase the loading area. The recycled plastic pellets could be produced more and the plastic tanks production would be increased by 35%, which would be able to reduce the environmental impact on using plastic pellets.

5.2 Suggestions

The results of life cycle impact assessment of HDPE drums produced by blow molding method showed that the process causing the major impact was the raw material production. Two modifications of plastic pellets production were tested, which were 1) reducing proportion of plastic scrap in the production process to increase the production efficiency and 2) specifying the drum collection area to increase the quantity of recycled plastic pellets production and to reduce the environmental impact due to the transportation of drums. Such modification could increase the eco-efficiency for 1.40 times comparing to the reference database.

Although the increasing proportion of recycled secondary plastic pellets in the production process was able to reduce the environmental impact, the recycle plastic pellets might be contaminated and impured due to the former used which might affect on the quality of the product. Furthermore, the application of bioplastic pellets as the ingredient could also reduce the environmental impact, especially in the disposal stage. However, bioplastic pellets are more expensive than other plastic pellets and have limitation for some packaging industries, especially the chemical products containers in this study required chemical resistance containers. Therefore, the manufacturers should test the quality of the containers containing new ingredients or plastic pellet types in order to optimize both product quality and eco-efficiency of production for the suitable application.

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APPENDICES

APPENDIX A
LCI DATA OF HDPE VIRGIN PELLETS

Table A.1 LCI data of HDPE virgin pellets from MTECH

Input			Output		
Substance	Amount	Unit	Substance	Amount	Unit
Raw Material			Emissions to air		
Aluminium	4.38E-05	Kg.	Arsenic	3.96E-15	Kg.
Coal etc., extracted for use	1.28E-05	Kg.	Cadmium	3.27E-16	Kg.
Coal, brown	2.82E-04	Kg.	Carbon dioxide	5.42E+00	Kg.
Copper	9.07E-06	Kg.	Chromium	7.20E-15	Kg.
Gas, natural gas liquid, in ground	5.22E-02	Kg.	Dinitrogen monoxide	1.23E-05	Kg.
Gas, natural, in ground (0.8 kg/m3)	6.53E-01	Kg.	Hydrocarbons, unspecified	7.67E-07	Kg.
Lead	3.34E-07	Kg.	Lead	1.90E-14	Kg.
Oil reserves	3.22E-04	Kg.	Mercury	4.78E-15	Kg.
Oil, crude	2.31E+00	Kg.	Methane	2.42E-03	Kg.
Uranium	3.48E-09	Kg.	Nickel	8.09E-15	Kg.
Zinc	1.85E-06	Kg.	Nitrogen oxides	4.56E-03	Kg.
			Nitrogen oxides (mobile source)	3.49E-07	Kg.
			NMHC	8.71E-12	Kg.
			NMVOC	2.57E-08	Kg.
			Sulfur dioxide	7.08E-03	Kg.
			Sulfur monoxide	1.47E-03	Kg.

Table A.1 LCI data of HDPE virgin pellets from MTECH (cont.)

Input			Output		
Substance	Amount	Unit	Substance	Amount	Unit
			Emissions to water		
			Arsenic	4.40E-10	Kg.
			BOD5	2.92E-05	Kg.
			Cadmium	9.19E-09	Kg.
			Chromium	9.26E-08	Kg.
			COD	1.31E+00	Kg.
			Lead	9.13E-08	Kg.
			Mercury	6.80E-10	Kg.
			Nickel	9.13E-08	Kg.
			Nitrogen, total	6.18E-06	Kg.
			Phenol	5.37E-10	Kg.
			Waste		
			Municipal waste landfill	1.75E-02	Kg.
			Plastic waste	6.83E-09	Kg.
			Rubbles	1.36E-08	Kg.
			Slags	1.75E-05	Kg.
			Sludge	3.77E-04	Kg.
			Waste, industrial	1.03E-02	Kg.
			Waste, nuclear, low-level active	2.44E-09	Kg.

APPENDIX B

STATION OF COLLECTION POSTCONSUMER PLASTIC DRUM

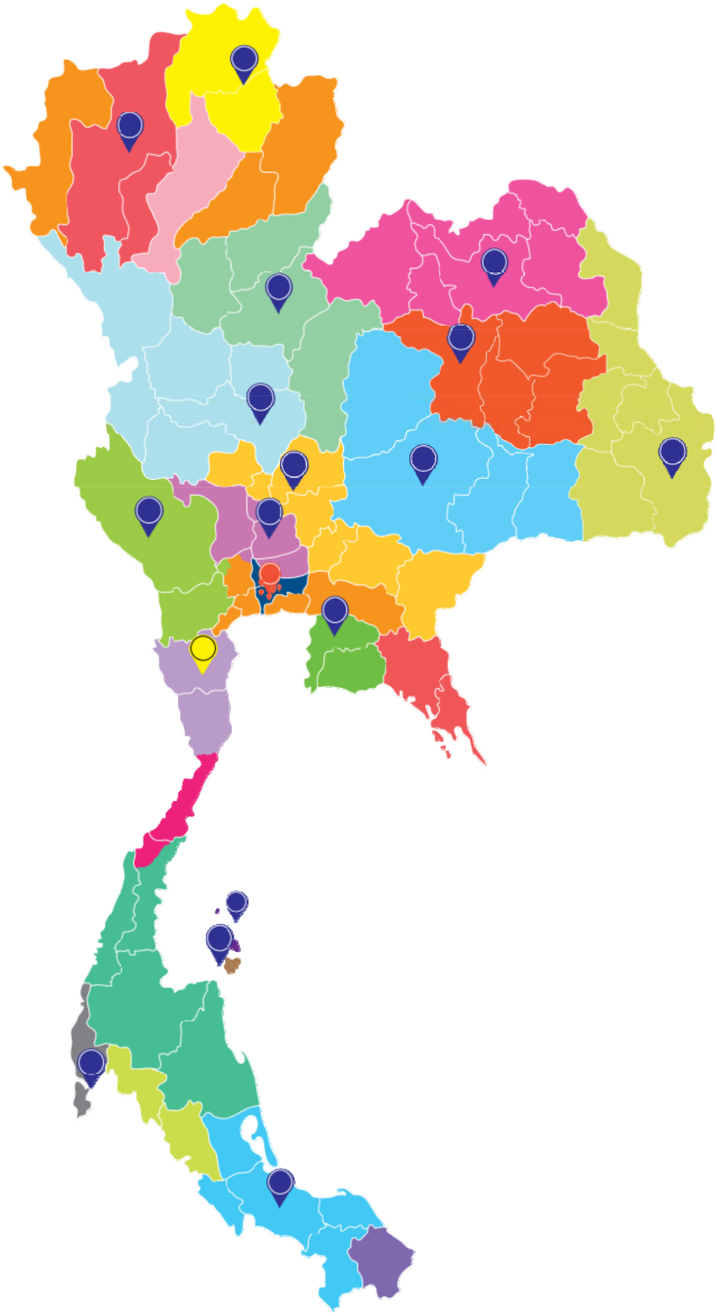

Figure B.1 Station of collection postconsumer plastic drum

Table B.1 Station of collection postconsumer plastic drum

Station	District	Province	Distance(Km.)
Station 1	Huai Khwang	Bangkok	114.74
Station 2	Huai Khwang	Bangkok	114.74
Station 3	Huai Khwang	Bangkok	114.74
Station 4	Don Sak	Suratthani	599.92
Station 5	Cha-am	Phetchaburi	61.34
Station 6	Mueang	Chiang Mai	778.27
Station 7	Bang Lamung	Chon Buri	229.34
Station 8	Mueang	Phuket	730.07
Station 9	Hat Yai	Songkhla	826.58
Station 10	Chom Thong	Bangkok	97.06
Station 11	Huai Khwang	Bangkok	114.74
Station 12	Huai Khwang	Bangkok	114.74
Station 13	Mueang	Chiang Rai	874.80
Station 14	Mueang	Phitsanulok	465.61
Station 15	Mueang	Nakhon Ratchasima	360.48
Station 16	Sao Hai	Saraburi	218.19
Station 17	Bang Pa-in	Ayutthaya	163.44
Station 18	Hat Yai	Songkhla	826.58
Station 19	Mueang	Udon Thani	671.36
Station 20	Tha Muang	Kanchanaburi	110.63
Station 21	Ban Haet	Khon Kaen	521.87
Station 22	Mueang	Suratthani	536.24
Station 23	Mueang	Ubon Ratchathani	703.84
Station 24	Don Sak	Suratthani	599.92
Station 25	Mueang	Nakhon Sawan	336.30

Table B.2 Distance of plastic drum collection process with Lorry transport, 4 wheels

Station	Distance (Km.)	Collection of plastic drums(July 2014 - June 2015)(Kg)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Station 1	114.74	1447.73	1692.74	1170.26	1047.20	1650.23	1624.50	1369.41	2037.33	1409.69	1238.51	539.26	1312.00
Station 2	114.74	2113.41	1981.39	1992.58	2879.79	2545.27	2982.72	2882.03	2837.28	2874.20	3026.35	1001.33	2526.00
Station 3	114.74	1536.11	1219.49	1413.04	1375.01	1414.16	1423.11	1908.67	1278.79	1557.37	1373.89	576.18	70.00
Station 5	61.34	341.23	161.11	13.43	162.23	144.33	198.03	309.91	83.91	136.49	133.14	69.37	268.00
Station 6	778.27	176.77	0.00	336.76	183.48	324.45	375.92	331.16	646.67	218.17	0.00	0.00	484.00
Station 7	229.34	426.26	519.12	485.56	493.39	431.86	534.79	295.36	245.02	532.55	691.42	134.26	39.00
Station 9	826.58	96.22	0.00	0.00	0.00	86.15	0.00	0.00	0.00	0.00	89.50	0.00	0.00
Station 10	97.06	45.87	83.91	0.00	0.00	192.43	0.00	0.00	41.40	119.71	34.68	0.00	237.00
Station 11	114.74	46.99	11.19	34.68	22.38	64.89	54.82	0.00	46.99	38.04	34.68	0.00	13.00
Station 12	114.74	180.13	161.11	140.97	127.54	213.69	184.60	191.31	162.23	181.25	159.99	53.70	109.00
Station 13	874.80	123.07	133.14	184.60	0.00	531.43	187.96	110.76	203.62	266.27	166.70	0.00	213.00
Station 14	465.61	109.64	102.93	257.32	0.00	245.02	110.76	0.00	97.34	344.59	0.00	0.00	0.00
Station 15	360.48	840.22	464.30	392.70	316.62	467.66	149.92	262.92	241.66	674.64	670.16	170.06	485.00

Table B.2 Distance of plastic drum collection process with Lorry transport, 4 wheels (cont.)

Station	Distance (Km.)	Collection of plastic drums(July 2014 - June 2015)(Kg)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Station 16	218.19	239.42	204.74	314.38	161.11	228.24	327.81	0.00	249.49	189.08	0.00	144.33	144.00
Station 17	163.44	151.04	156.63	184.60	151.04	167.82	126.42	159.99	151.04	111.88	157.75	124.19	0.00
Station 18	826.58	0.00	262.92	0.00	0.00	0.00	0.00	364.73	0.00	611.98	123.07	0.00	0.00
Station 19	671.36	96.22	26.85	39.16	170.06	29.09	0.00	0.00	59.30	0.00	0.00	0.00	45.00
Station 20	110.63	0.00	0.00	0.00	279.70	0.00	0.00	0.00	277.46	140.97	240.54	0.00	0.00
Station 21	521.87	22.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Station 22	536.24	189.08	0.00	0.00	315.50	206.98	0.00	0.00	0.00	123.07	0.00	0.00	0.00
Station 23	703.84	260.68	399.41	152.16	486.68	457.59	96.22	633.24	322.21	542.62	250.61	213.69	324.00
Station 24	599.92	550.45	0.00	0.00	137.61	0.00	305.43	0.00	292.01	0.00	194.67	0.00	0.00
Station 25	336.30	0.00	196.91	0.00	0.00	123.07	0.00	0.00	115.24	0.00	156.63	76.08	0.00
		9290.52	7979.28	7378.49	8376.46	9966.27	8952.64	9113.74	9767.12	10305.27	8982.85	3110.26	8424.00
		9.29	**7.98**	**7.38**	**8.38**	**9.97**	**8.95**	**9.11**	**9.77**	**10.31**	**8.98**	**3.11**	**8.42**

Table B.3 Distance of plastic drum collection process with Lorry transport, 6 wheels

Station	Distance	Collection of plastic drums(July 2014 - June 2015)(Kg)											
	(Km.)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Station 4	599.92	0.00	212.57	27.97	0.00	0.00	515.77	0.00	0.00	982.31	0.00	0.00	0.00
Station 8	730.07	472.13	318.86	803.30	0.00	1485.77	726.10	589.61	393.82	652.26	1354.87	0.00	678.00
		472.13	531.43	831.27	0.00	1485.77	1241.87	589.61	393.82	1634.57	1354.87	0.00	678.00
	0.47	**0.53**	**0.83**	**0.00**	**1.49**	**1.24**	**0.59**	**0.39**	**1.63**	**1.35**	**0.00**	**0.87**	**0.68**

APPENDIX C
CHARACTERIZATION, NORMALIZATION AND WEIGHTING FACTOR OF RECIPE 2008

Appendix C1 Characterization factor of ReCiPe2008

Table C.1 Characterization factor of freshwater eutrophication (FEP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint (H) kg P eq	Endpoint (Ecosystems)(H) species.yr
soil	Phosphate	kg	3.30E-01	1.47E-08
soil	Phosphoric acid	kg	3.20E-01	1.42E-08
soil	Phosphorus	kg	1.00E+00	4.44E-08
soil	Phosphorus	kg	1.00E+00	4.44E-08
soil	Phosphorus	kg	1.00E+00	4.44E-08
soil	Phosphorus	kg	1.00E+00	4.44E-08
soil	Phosphorus pentoxide	kg	4.40E-01	1.95E-08
soil	Phosphorus, total	kg	1.00E+00	4.44E-08
soil	Manure, applied	kg	5.00E-02	2.22E-09
soil	fertiliser, applied	kg	5.30E-02	2.35E-09
water	Phosphoric acid	kg	3.20E-01	1.42E-08
water	Phosphorus pentoxide	kg	4.40E-01	1.95E-08
water	Phosphorus, total	kg	1.00E+00	4.44E-08
water	Phosphoric acid	kg	0.00E+00	0.00E+00
water	Phosphorus pentoxide	kg	0.00E+00	0.00E+00
water	Phosphorus, total	kg	0.00E+00	0.00E+00
water	Phosphate	kg	3.30E-01	1.47E-08
water	Phosphorus	kg	0.00E+00	0.00E+00
water	Phosphorus	kg	1.00E+00	4.44E-08
water	Phosphate	kg	0.00E+00	0.00E+00

Table C.2 Characterization factor of marine eutrophication (MEP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H) kg N eq
air	Ammonium, ion	kg	0.087
air	Ammonia	kg	0.092
air	Cyanide	kg	0.000
air	Nitrate	kg	0.028
air	Nitrogen dioxide	kg	0.039
air	Nitrogen oxides	kg	0.039
air	Nitric oxide***	kg	0.060
soil	Manure, applied (N component)	kg	0.079
soil	Fertiliser, applied (N component)	kg	0.073
water	Ammonia	kg	0.824
water	Ammonia, as N	kg	1.000
water	Ammonia	kg	1.177
water	Ammonia, as N	kg	1.429
water	Nitrogen, total	kg	1.429
water	Ammonium, ion	kg	1.114
water	Cyanide	kg	0.771
water	Nitrate	kg	0.329
water	Nitrite	kg	0.429
water	Nitrogen	kg	1.429
water	Nitrogen, organic bound	kg	1.429
water	Ammonium, ion	kg	0.780
water	Cyanide	kg	0.540
water	Nitrate	kg	0.230
water	Nitrite	kg	0.300
water	Nitrogen	kg	1.000
water	Nitrogen, organic bound	kg	1.000
water	Nitrogen, total	kg	1.000

***Assumed equal to NO_2

Table C3 Characterization factor of climate change (GWP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint (H)	Endpoint (Human health)(H)	Endpoint (Ecosystems)(H)
			kg CO_2 eq	DALY	species.yr
air	Methane, iodotrifluoro-	kg	4.00E-01	5.60E-07	3.17E-09
air	Carbon dioxide	kg	1.00E+00	1.40E-06	7.93E-09
air	Carbon dioxide, fossil	kg	1.00E+00	1.40E-06	7.93E-09
air	Carbon dioxide, land transformation	kg	1.00E+00	1.40E-06	7.93E-09
air	Dimethylether	kg	1.00E+00	1.40E-06	7.93E-09
air	Methane, dibromo-	kg	1.54E+00	2.16E-06	1.22E-08
air	Methyl bromide	kg	5.00E+00	7.00E-06	3.96E-08
air	Methylene chloride	kg	8.70E+00	1.22E-05	6.90E-08
air	Halogenated hydrocarbons, chlorinated	kg	1.06E+01	1.48E-05	8.40E-08
air	Ether, 2,2,3,3,3-Pentafluoropropyl methyl-, HFE-365mcf3	kg	1.10E+01	1.54E-05	8.72E-08
air	HFE-263fb2	kg	1.10E+01	1.54E-05	8.72E-08
air	Ethane, fluoro-, HFC-161	kg	1.20E+01	1.68E-05	9.51E-08
air	Methyl chloride	kg	1.30E+01	1.82E-05	1.03E-07
air	Methane, biogenic	kg	2.23E+01	3.12E-05	1.76E-07
air	Methane, fossil	kg	2.50E+01	3.50E-05	1.98E-07
air	Methanec	kg	2.50E+01	3.50E-05	1.98E-07

Table C.3 Characterization factor of climate change (GWP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint	Endpoint	
			(H)	(Human health)(H)	(Ecosystems)(H)
			kg CO_2 eq	DALY	species.yr
air	Chloroform	kg	3.10E+01	4.34E-05	2.46E-07
air	Ethane, 1,2-difluoro-, HFC-152	kg	5.30E+01	7.42E-05	4.20E-07
air	HFE-569sf2	kg	5.90E+01	8.26E-05	4.68E-07
air	HCFC-123	kg	7.70E+01	1.08E-04	6.11E-07
air	Methane, fluoro-, HFC-41	kg	9.20E+01	1.29E-04	7.29E-07
air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356mec3	kg	1.01E+02	1.41E-04	8.01E-07
air	HFE-356pcc3	kg	1.10E+02	1.54E-04	8.72E-07
air	HCFC-225ca	kg	1.22E+02	1.71E-04	9.67E-07
air	HFC-152a	kg	1.24E+02	1.74E-04	9.83E-07
air	Methyl chloroform	kg	1.46E+02	2.04E-04	1.16E-06
air	Methane, dichlorofluoro-, HCFC-21	kg	1.51E+02	2.11E-04	1.20E-06
air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf2	kg	2.65E+02	3.71E-04	2.10E-06
air	Ether, difluoromethyl 2,2,2-trifluoroethyl-, HFE-245fa1	kg	2.86E+02	4.00E-04	2.27E-06
air	(HFE-7100)	kg	2.97E+02	4.16E-04	2.35E-06

Table C.3 Characterization factor of climate change (GWP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint	Endpoint	
			(H)	(Human health)(H)	(Ecosystems)(H)
			kg CO_2 eq	DALY	species.yr
air	Nitrous oxide	kg	2.98E+02	4.17E-04	2.36E-06
air	HCFE-235da2	kg	3.50E+02	4.90E-04	2.78E-06
air	Ethane, 1,1,2-trifluoro-, HFC-143	kg	3.53E+02	4.94E-04	2.80E-06
air	HFE-254cb2	kg	3.59E+02	5.03E-04	2.85E-06
air	Ether, 1,1,2,2-Tetrafluoroethyl 2,2,2-trifluoroethyl-, HFE-347mcf2	kg	3.74E+02	5.24E-04	2.97E-06
air	Methane, bromodifluoro-, Halon 1201	kg	4.04E+02	5.66E-04	3.20E-06
air	Ether, 1,2,2-trifluoroethyl trifluoromethyl-, HFE-236fa	kg	4.87E+02	6.82E-04	3.86E-06
air	Ether, 1,1,2,3,3,3-Hexafluoropropyl methyl-, HFE-356pcf3	kg	5.02E+02	7.03E-04	3.98E-06
air	HFE-338mcf2	kg	5.52E+02	7.73E-04	4.38E-06
air	Ether, ethyl 1,1,2,2-tetrafluoroethyl-, HFE-374pc2	kg	5.57E+02	7.80E-04	4.42E-06
air	HFE-347mcc3	kg	5.75E+02	8.05E-04	4.56E-06
air	HFE-347pcf2	kg	5.80E+02	8.12E-04	4.60E-06
air	HCFC-225cb	kg	5.95E+02	8.33E-04	4.72E-06
air	HCFC-124	kg	6.09E+02	8.53E-04	4.83E-06
air	HFE-245fa2	kg	6.59E+02	9.23E-04	5.23E-06

Table C.3 Characterization factor of climate change (GWP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint (H)	Endpoint (Human health)(H)	Endpoint (Ecosystems)(H)
			kg CO_2 eq	DALY	species.yr
air	HFC-32	kg	6.75E+02	9.45E-04	5.35E-06
air	Propane, 1,1,2,2,3-pentafluoro-, HFC-245ca	kg	6.93E+02	9.70E-04	5.49E-06
air	HFE-245cb2	kg	7.08E+02	9.91E-04	5.61E-06
air	HCFC-141b	kg	7.25E+02	1.02E-03	5.75E-06
air	HFE-143a	kg	7.56E+02	1.06E-03	5.99E-06
air	HFC-365mfc	kg	7.94E+02	1.11E-03	6.30E-06
air	HFE-329mcc2	kg	9.19E+02	1.29E-03	7.29E-06
air	Ether, 1,2,2-trifluoroethyl trifluoromethyl-, HFE-236ea2	kg	9.89E+02	1.38E-03	7.84E-06
air	HFC-245fa	kg	1.03E+03	1.44E-03	8.17E-06
air	Ethane, 1,1,2,2-tetrafluoro-, HFC-134	kg	1.10E+03	1.54E-03	8.72E-06
air	Propane, 1,1,1,2,2,3-hexafluoro-, HFC-236cb	kg	1.34E+03	1.88E-03	1.06E-05
air	Propane, 1,1,1,2,3,3-hexafluoro-, HFC-236ea	kg	1.37E+03	1.92E-03	1.09E-05
air	Carbon tetrachloride	kg	1.40E+03	1.96E-03	1.11E-05
air	HFC-134a	kg	1.43E+03	2.00E-03	1.13E-05
air	HFE-338pcc13 (HG-01)	kg	1.50E+03	2.10E-03	1.19E-05
air	HFE-227EA	kg	1.54E+03	2.16E-03	1.22E-05

Table C.3 Characterization factor of climate change (GWP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint (H) kg CO_2 eq	Endpoint (Human health)(H) DALY	Endpoint (Ecosystems)(H) species.yr
air	Halon-2402	kg	1.64E+03	2.30E-03	1.30E-05
air	HFC-43-10mee	kg	1.64E+03	2.30E-03	1.30E-05
air	HCFC-22	kg	1.81E+03	2.53E-03	1.44E-05
air	HFE-43-10pccc124 (H-Galden1040x)	kg	1.87E+03	2.62E-03	1.48E-05
air	Halon-1211	kg	1.89E+03	2.65E-03	1.50E-05
air	HCFC-142b	kg	2.31E+03	3.23E-03	1.83E-05
air	HFE-236ca12 (HG-10)	kg	2.80E+03	3.92E-03	2.22E-05
air	HFC-227ea	kg	3.22E+03	4.51E-03	2.55E-05
air	HFC-125	kg	3.50E+03	4.90E-03	2.78E-05
air	HFC-143a	kg	4.47E+03	6.26E-03	3.54E-05
air	CFC-11	kg	4.75E+03	6.65E-03	3.77E-05
air	CFC-113	kg	6.13E+03	8.58E-03	4.86E-05
air	HFE-134	kg	6.32E+03	8.85E-03	5.01E-05
air	Halon-1301	kg	7.14E+03	1.00E-02	5.66E-05
air	CFC-115	kg	7.37E+03	1.03E-02	5.84E-05
air	PFC-14	kg	7.39E+03	1.03E-02	5.86E-05

Table C.3 Characterization factor of climate change (GWP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint	Endpoint	
			(H)	(Human health)(H)	(Ecosystems)(H)
			kg CO_2 eq	DALY	species.yr
air	PFC-9-1-18	kg	7.50E+03	1.05E-02	5.95E-05
air	PFC-218	kg	8.83E+03	1.24E-02	7.00E-05
air	PFC-3-1-10	kg	8.86E+03	1.24E-02	7.03E-05
air	Pentane, perfluoro-	kg	9.16E+03	1.28E-02	7.26E-05
air	PFC-4-1-12	kg	9.16E+03	1.28E-02	7.26E-05
air	PFC-5-1-14	kg	9.30E+03	1.30E-02	7.37E-05
air	HFC-236fa	kg	9.81E+03	1.37E-02	7.78E-05
air	CFC-114	kg	1.00E+04	1.40E-02	7.93E-05
air	PFC-318	kg	1.03E+04	1.44E-02	8.17E-05
air	PFPMIE	kg	1.03E+04	1.44E-02	8.17E-05
air	CFC-12	kg	1.09E+04	1.53E-02	8.64E-05
air	PFC-116	kg	1.22E+04	1.71E-02	9.67E-05
air	CFC-13	kg	1.44E+04	2.02E-02	1.14E-04
air	HFC-23	kg	1.48E+04	2.07E-02	1.17E-04
air	HFE-125	kg	1.49E+04	2.09E-02	1.18E-04
air	Nitrogen trifluoride	kg	1.72E+04	2.41E-02	1.36E-04

Table C.3 Characterization factor of climate change (GWP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint	Endpoint	
			(H)	(Human health)(H)	(Ecosystems)(H)
			kg CO_2 eq	DALY	species.yr
air	trifluoromethyl sulphur pentafluoride	kg	1.77E+04	2.48E-02	1.40E-04
air	Sulphur hexafluoride	kg	2.28E+04	3.19E-02	1.81E-04

Table C.4 Characterization factor of ozone depletion (ODP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	End point(H)
			kg CFC-11 eq	HH (DALY)
air	CFC-11 (R)	kg	1.00E+00	1.76E-03
air	CFC-12	kg	1.00E+00	1.76E-03
air	CFC-113	kg	1.00E+00	1.76E-03
air	CFC-114	kg	9.40E-01	1.65E-03
air	CFC-115	kg	4.40E-01	7.74E-04
air	HCFC-123	kg	2.00E-02	7.30E-05
air	HCFC-124	kg	2.00E-02	7.30E-05
air	HCFC-141b	kg	1.20E-01	4.38E-04
air	HCFC-142b	kg	7.00E-02	2.56E-04
air	HCFC-22	kg	5.00E-02	1.82E-04
air	HCFC-225ca	kg	2.00E-02	7.30E-05
air	HCFC-225cb	kg	3.00E-02	1.10E-04
air	Halon-1201 (HBFC 1201)	kg	1.40E+00	3.70E-03
air	Halon-1202	kg	1.30E+00	3.43E-03
air	Halon-1211	kg	6.00E+00	1.58E-02
air	Halon-1301	kg	1.20E+01	3.17E-02
air	Halon-2311 (HBFC 2311)	kg	1.40E-01	3.70E-04
air	Halon-2401 (HBFC 2401)	kg	2.50E-01	6.60E-04
air	Halon-2402	kg	6.00E+00	1.58E-02
air	Carbontetrachloride	kg	7.30E-01	2.41E-03
air	Methylchloroform	kg	1.20E-01	5.29E-04
air	Methylbromide	kg	3.80E-01	1.79E-03
air	Methylbromide	kg	3.80E-01	1.79E-03
air	Methylchloride	kg	2.00E-02	0.00E+00
air	HCFC-140	kg	1.20E-01	5.29E-04
air	Halogenated hydrocarbons, chlorinated	kg	6.17E-03	0.00E+00

Table C.5 Characterization factor of terrestrial acidification(TAP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg SO_2 eq	EH(species.yr)
air	NOx to air	kg	0.56	3.25E-09
air	NH3 to air	kg	2.45	1.42E-08
air	SO2 to air	kg	1	5.80E-09
air	Sulfur oxides	kg	1	5.80E-09
air	Sulfur monoxide	kg	1	5.80E-09
air	Nitrogen dioxide	kg	0.56	3.25E-09

Table C.6 Characterization factor of photochemical oxidant formation (POFP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg NMVOC	HH(DALY)
air	NMVOC	kg	1.000	3.9E-08
air	Nitrogen oxides	kg	1.000	3.9E-08
air	Benzaldehyde	kg	-0.155	-6.1E-09
air	Methyl Chloride	kg	0.008	3.3E-10
air	Methane	kg	0.010	4.0E-10
air	1,1,1-trichloroethane	kg	0.015	5.9E-10
air	Trichloromethane	kg	0.039	1.5E-09
air	Dimethyl carbonate	kg	0.042	1.6E-09
air	Carbon Monoxide	kg	0.046	1.8E-09
air	Methyl Formate	kg	0.046	1.8E-09
air	tetrachloroethylene	kg	0.049	1.9E-09
air	Formic acid	kg	0.054	2.1E-09
air	sulphur dioxide	kg	0.081	3.2E-09
air	tertiary-Butyl Acetate	kg	0.090	3.5E-09
air	Methyl Acetate	kg	0.100	3.9E-09
air	Dichloromethane	kg	0.115	4.5E-09
air	Acetylene	kg	0.144	5.6E-09

Table C.6 Characterization factor of photochemical oxidant formation (POFP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg NMVOC	HH(DALY)
air	Acetone	kg	0.159	6.2E-09
air	Acetic acid	kg	0.164	6.4E-09
air	tertiary-Butanol	kg	0.179	7.0E-09
air	Ethane	kg	0.208	8.1E-09
air	Methanol	kg	0.236	9.2E-09
air	styrene	kg	0.240	9.4E-09
air	Propanoic acid	kg	0.253	9.9E-09
air	Dimethoxy methane	kg	0.277	1.1E-08
air	Neopentane	kg	0.292	1.1E-08
air	Methyl tert-Butyl Ether	kg	0.296	1.2E-08
air	Propane	kg	0.297	1.2E-08
air	isopropanol	kg	0.318	1.2E-08
air	Dimethyl Ether	kg	0.319	1.2E-08
air	Ethyl Acetate	kg	0.353	1.4E-08
air	isopropyl acetate	kg	0.356	1.4E-08
air	Benzene	kg	0.368	1.4E-08
air	2-Methylbutan-2-ol	kg	0.385	1.5E-08
air	2,2-Dimethylbutane	kg	0.407	1.6E-08
air	Ethyl- trans-Butyl Ether	kg	0.412	1.6E-08
air	1-Butyl Acetate	kg	0.454	1.8E-08
air	sec-Butyl Acetate	kg	0.465	1.8E-08
air	1-Propylacetate	kg	0.476	1.9E-08
air	Cyclohexane	kg	0.490	1.9E-08
air	Cyclohexanone	kg	0.505	2.0E-08
air	2-Methoxy-Ethanol	kg	0.519	2.0E-08
air	Diacetone alcohol	kg	0.519	2.0E-08
air	isobutane	kg	0.519	2.0E-08
air	Methyl tert-butylketone	kg	0.546	2.1E-08

Table C.6 Characterization factor of photochemical oxidant formation (POFP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg NMVOC	HH(DALY)
air	Trichloroethylene	kg	0.549	2.1E-08
air	Butane	kg	0.595	2.3E-08
air	1-Methoxy-2-propanol	kg	0.600	2.3E-08
air	Dodecane	kg	0.603	2.4E-08
air	isobutanol	kg	0.608	2.4E-08
air	3-Methylhexane	kg	0.615	2.4E-08
air	Methyl-Isopropylketone	kg	0.615	2.4E-08
air	2-butanone	kg	0.630	2.5E-08
air	Ethylene Glycol	kg	0.630	2.5E-08
air	1-Undecane	kg	0.649	2.5E-08
air	Decane	kg	0.649	2.5E-08
air	2-Ethoxy-Ethanol	kg	0.652	2.5E-08
air	trans-dichloroethene	kg	0.662	2.6E-08
air	Pentane	kg	0.667	2.6E-08
air	Diisopropylether	kg	0.672	2.6E-08
air	Ethanol	kg	0.674	2.6E-08
air	sec-Butanol	kg	0.676	2.6E-08
air	isopentane	kg	0.684	2.7E-08
air	3-Methylbutan-2-ol	kg	0.686	2.7E-08
air	2-Methylhexane	kg	0.694	2.7E-08
air	Diethylketone	kg	0.699	2.7E-08
air	Nonane	kg	0.699	2.7E-08
air	2-Methylpentane	kg	0.709	2.8E-08
air	3-Methylbutan-1-ol	kg	0.731	2.9E-08
air	Diethyl Ether	kg	0.752	2.9E-08
air	cis-Dichloroethene	kg	0.755	2.9E-08
air	Octane	kg	0.765	3.0E-08

Table C.6 Characterization factor of photochemical oxidant formation (POFP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg NMVOC	HH(DALY)
air	Propylene Glycol	kg	0.772	3.0E-08
air	1-Butoxypropanol	kg	0.782	3.1E-08
air	3-Methylpentane	kg	0.809	3.2E-08
air	Hexane	kg	0.814	3.2E-08
air	2-Butoxy-Ethanol	kg	0.816	3.2E-08
air	2-Methylbutan-1-ol	kg	0.826	3.2E-08
air	Methyl Isobutyl Ketone	kg	0.828	3.2E-08
air	Heptane	kg	0.834	3.3E-08
air	isopropyl benzene	kg	0.845	3.3E-08
air	isobutyraldehyde	kg	0.868	3.4E-08
air	Cyclohexanol	kg	0.875	3.4E-08
air	Formaldehyde	kg	0.877	3.4E-08
air	2.3- Dimethylbutane	kg	0.914	3.6E-08
air	Methyl propyl Ketone	kg	0.926	3.6E-08
air	1-Propanol	kg	0.948	3.7E-08
air	Hexan-2-one	kg	0.966	3.8E-08
air	3-Pentanol	kg	1.005	3.9E-08
air	Hexan-3-one	kg	1.012	3.9E-08
air	1-Butanol	kg	1.047	4.1E-08
air	isobutene	kg	1.059	4.1E-08
air	1-Propyl Benzene	kg	1.074	4.2E-08
air	Toluene	kg	1.076	4.2E-08
air	Acetaldehyde	kg	1.083	4.2E-08
air	3-Methyl-1-Butene	kg	1.133	4.4E-08
air	Ethylbenzene	kg	1.233	4.8E-08
air	Pentanaldehyde	kg	1.292	5.0E-08
air	2-Methyl-1-Butene	kg	1.302	5.1E-08
air	Butyraldehyde	kg	1.343	5.2E-08

Table C.6 Characterization factor of photochemical oxidant formation (POFP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg NMVOC	HH(DALY)
air	Propionaldehyde	kg	1.348	5.3E-08
air	2-Methyl-2-Butene	kg	1.422	5.5E-08
air	1,3-Butadiene	kg	1.438	5.6E-08
air	1-Hexene	kg	1.476	5.8E-08
air	ortho-Ethyltoluene	kg	1.517	5.9E-08
air	para-Ethyltoluene	kg	1.530	6.0E-08
air	1-Pentene	kg	1.650	6.4E-08
air	Ethylene	kg	1.689	6.6E-08
air	para-Xylene	kg	1.706	6.7E-08
air	meta-Ethyltoluene	kg	1.721	6.7E-08
air	ortho-Xylene	kg	1.779	6.9E-08
air	meta-Ethyltoluene	kg	1.721	6.7E-08
air	ortho-Xylene	kg	1.779	6.9E-08
air	cis-2-Hexene	kg	1.806	7.0E-08
air	trans-2-Hexene	kg	1.813	7.1E-08
air	1-Butene	kg	1.823	7.1E-08
air	isoprene	kg	1.845	7.2E-08
air	meta-Xylene	kg	1.872	7.3E-08
air	trans-2-Pentene	kg	1.887	7.4E-08
air	cis-2-Pentene	kg	1.894	7.4E-08
air	Propylene	kg	1.897	7.4E-08
air	trans-2-Butene	kg	1.912	7.5E-08
air	cis-2-Butene	kg	1.936	7.5E-08
air	1,2,3-Trimethyl Benzene	kg	2.140	8.3E-08
air	1,2,4-trimethylbenzene	kg	2.159	8.4E-08
air	Toluene, 3,5-diethyl-	kg	2.188	8.5E-08
air	Benzene, 3,5-dimethylethyl-	kg	2.230	8.7E-08

Table C.6 Characterization factor of photochemical oxidant formation (POFP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg NMVOC	HH(DALY)
air	1,3,5-trimethylbenzene	kg	2.333	9.1E-08
air	Halogenated hydrocarbons, chlorinated	kg	0.125	4.9E-09
air	Hydrocarbons, aliphatic, alkanes, cyclic	kg	0.476	1.9E-08
air	Hydrocarbons, aromatic	kg	0.397	1.5E-08
air	Sulfur oxides	kg	0.081	3.2E-09
Air	Aldehydes, unspecified	kg	0.927	3.6E-08
Air	Carbon monoxide, biogenic	kg	0.0456	1.8E-09
Air	Carbon monoxide, fossil	kg	0.0456	1.8E-09
Air	Methane, biogenic	kg	0.0101	3.9E-10
Air	Methane, fossil	kg	0.0101	3.9E-10
Air	Nitrogen dioxide	kg	1	3.9E-08
Air	Pentanal	kg	1.29	5.0E-08
Air	Sulfur monoxide	kg	0.0811	3.2E-09

Table C.7 Characterization factor of particulate matter formation (PMFP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg PM_{10} eq	HH(DALY)
air	Particulates, < 10 um	kg	1.00E+00	2.60E-04
air	Ammonia	kg	3.20E-01	8.32E-05
air	Nitrogen oxides	kg	2.20E-01	5.72E-05
air	Sulfur dioxide	kg	2.00E-01	5.20E-05
air	NMVOC	kg	0.00E+00	0.00E+00
air	Sulfur oxides	kg	2.00E-01	5.20E-05

Table C.7 Characterization factor of particulate matter formation (PMFP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg PM_{10} eq	HH(DALY)
air	Sulfur monoxide	kg	2.00E-01	5.20E-05
air	Nitrogen dioxide	kg	2.20E-01	5.72E-05
air	Particulates, < 10 um (mobile)	kg	1.00E+00	2.60E-04
air	Particulates, < 10 um (stationary)	kg	1.00E+00	2.60E-04
air	Particulates, < 2.5 um	kg	1.00E+00	2.60E-04
air	Particulates, > 2.5 um, and < 10um	kg	1.00E+00	2.60E-04

Table C.8 Characterization factor of ionising radiation (IRP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg U^{235} eq	HH(DALY)
air	Actinides, radioactive, unspecified	kBq	2.51E+00	4.12E-08
water	Americium-241 (Am-241)	kBq	1.50E+00	2.46E-08
water	Antimony-124 (Sb-124)	kBq	3.86E-02	6.33E-10
water	Antimony-125 (Sb-125)	kBq	7.00E-04	1.15E-11
air	Carbon-14 (C-14)	kBq	1.00E+01	1.64E-07
water	Carbon-14 (C-14)	kBq	5.57E-02	9.14E-10
air	Cesium-134 (Cs-134)	kBq	5.64E-01	9.25E-09
water	Cesium-134 (Cs-134)	kBq	6.79E+00	1.11E-07
water	Cesium-134 (Cs-134)	kBq	3.71E-03	6.09E-11
air	Cesium-137 (Cs-137)	kBq	6.36E-01	1.04E-08
water	Cesium-137 (Cs-137)	kBq	7.86E+00	1.29E-07
water	Cesium-137 (Cs-137)	kBq	3.71E-03	6.09E-11
air	Cobalt-58 (Co-58)	kBq	2.00E-02	3.28E-10

Table C.8 Characterization factor of ionising radiation (IRP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg U^{235} eq	HH(DALY)
water	Cobalt-58 (Co-58)	kBq	1.93E-03	3.16E-11
air	Cobalt-60 (Co-60)	kBq	7.86E-01	1.29E-08
water	Cobalt-60 (Co-60)	kBq	2.07E+00	3.40E-08
water	Cobalt-60 (Co-60)	kBq	1.86E-02	3.05E-10
water	Curium alpha (Cm alpha)	kBq	2.71E+00	4.45E-08
air	Tritium (H-3)	kBq	6.79E-04	1.11E-11
water	Tritium (H-3)	kBq	2.14E-05	3.51E-13
water	Tritium (H-3) into the sea	kBq	3.29E-06	5.39E-14
air	Iodine-129 (I-129)	kBq	4.43E+01	7.26E-07
water	Iodine-129 (I-129)	kBq	4.71E+00	7.73E-08
air	Iodine-131 (I-131)	kBq	7.14E-03	1.17E-10
water	Iodine-131 (I-131)	kBq	2.36E-02	3.87E-10
air	Iodine-133 (I-133)	kBq	4.43E-04	7.26E-12
air	Krypton-85 (Kr-85)	kBq	6.64E-06	1.09E-13
air	Lead-210 (Pb-210)	kBq	7.14E-02	1.17E-09
water	Manganese-54 (Mn-54)	kBq	1.50E-02	2.46E-10
air	Noble gases, radioactive, unspecified	kBq	6.18E-09	1.01E-16
air	Plutonium-238 (Pu-238)	kBq	3.14E+00	5.15E-08
air	Plutonium alpha (Pu alpha)	kBq	3.93E+00	6.44E-08
water	Plutonium alpha (Pu alpha)	kBq	3.50E-01	5.74E-09
air	Polonium-210 (Po-210)	kBq	7.14E-02	1.17E-09
air	Radium-226 (Ra-226)	kBq	4.29E-02	7.03E-10
water	Radium-226 (Ra-226)	kBq	6.07E-03	9.96E-11
air	Radon-222 (Rn-222)	kBq	1.14E-03	1.87E-11
water	Ruthenium-106 (Ru-106)	kBq	6.79E-03	1.11E-10
water	Silver-110 (Ag-110m)	kBq	2.36E-02	3.87E-10

Table C.8 Characterization factor of ionising radiation (IRP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg U^{235} eq	HH(DALY)
water	Strontium-90 (Sr-90)	kBq	1.93E-04	3.16E-12
air	Thorium-230 (Th-230)	kBq	2.14E+00	3.51E-08
water	Uranium alpha	kBq	1.07E-03	1.76E-11
water	Uranium alpha	kBq	1.07E-01	1.76E-09
air	Uranium alpha	kBq	3.86E-01	6.33E-09
air	Uranium-234 (U-234)	kBq	4.57E+00	7.50E-08
water	Uranium-234 (U-234)	kBq	1.14E-01	1.87E-09
water	Uranium-234 (U-234)	kBq	1.07E-03	1.76E-11
air	Uranium-235 (U-235)	kBq	1.00E+00	1.64E-08
water	Uranium-235 (U-235)	kBq	1.07E-01	1.76E-09
water	Uranium-235 (U-235)	kBq	1.14E-03	1.87E-11
air	Uranium-238 (U-238)	kBq	3.86E-01	6.33E-09
water	Uranium-238 (U-238)	kBq	1.07E-01	1.76E-09
water	Uranium-238 (U-238)	kBq	1.07E-03	1.76E-11
air	Xenon-133 (Xe-133)	kBq	6.71E-06	1.10E-13

Table C.9 Characterization factor of land occupation (ALOP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)		Endpoint(H)	
			Agricultural land occupation m^2a	Urban land occupation m^2a	Agricultural land occupation EQ(species.yr)	Urban land occupation EQ(species.yr)
raw	Occupation, arable	m^2a	1		2.0E-08	
raw	Occupation, arable, integrated	m^2a	1		2.0E-08	
raw	Occupation, arable, non-irrigated	m^2a	1		2.0E-08	
raw	Occupation, arable, non-irrigated, diverse-intensive	m^2a	1		2.1E-08	
raw	Occupation, arable, non-irrigated, fallow	m^2a	1		1.9E-08	
raw	Occupation, arable, non-irrigated, monotone-intensive	m^2a	1		2.1E-08	
raw	Occupation, arable, organic	m^2a	1		1.9E-08	
raw	Occupation, construction site	m^2a		1		2.1E-08
raw	Occupation, dump site	m^2a		1		2.1E-08
raw	Occupation, dump site, benthos	m^2a		1		2.1E-08
raw	Occupation, forest	m^2a	1		9.3E-09	
raw	Occupation, forest, extensive	m^2a	1		9.3E-09	

Table C.9 Characterization factor of land occupation (ALOP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)		Endpoint(H)	
			Agricultural land occupation m^2a	Urban land occupation m^2a	Agricultural land occupation EQ(species.yr)	Urban land occupation EQ(species.yr)
raw	Occupation, forest, intensive	m^2a	1		1.2E-08	
raw	Occupation, forest, intensive, clear-cutting	m^2a	1		1.6E-08	
raw	Occupation, forest, intensive, normal	m^2a	1		1.2E-08	
raw	Occupation, forest, intensive, short-cycle	m^2a	1		1.6E-08	
raw	Occupation, heterogeneous, agricultural	m^2a	1		1.9E-08	
raw	Occupation, industrial area	m^2a		1		2.1E-08
raw	Occupation, industrial area, benthos	m^2a		1		2.1E-08
raw	Occupation, industrial area, built up	m^2a		1		2.1E-08
raw	Occupation, industrial area, vegetation	m^2a		1		2.1E-08
raw	Occupation, mineral extraction site	m^2a		1		2.1E-08
raw	Occupation, pasture and meadow	m^2a	1		1.4E-08	

Table C.9 Characterization factor of land occupation (ALOP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)		Endpoint(H)	
			Agricultural land occupation m^2a	Urban land occupation m^2a	Agricultural land occupation EQ(species.yr)	Urban land occupation EQ(species.yr)
raw	Occupation, pasture and meadow, extensive	m^2a	1		1.4E-08	
raw	Occupation, pasture and meadow, intensive	m^2a	1		1.7E-08	
raw	Occupation, pasture and meadow, organic	m^2a	1		1.0E-08	
raw	Occupation, permanent crop	m^2a	1		1.6E-08	
raw	Occupation, permanent crop, fruit	m^2a	1		1.6E-08	
raw	Occupation, permanent crop, fruit, extensive	m^2a	1		1.2E-08	
raw	Occupation, permanent crop, fruit, intensive	m^2a	1		1.6E-08	
raw	Occupation, permanent crop, vine	m^2a	1		1.3E-08	

Table C.9 Characterization factor of land occupation (ALOP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)		Endpoint(H)	
			Agricultural land occupation m^2a	Urban land occupation m^2a	Agricultural land occupation EQ(species.yr)	Urban land occupation EQ(species.yr)
raw	Occupation, permanent crop, vine, extensive	m^2a	1		1.3E-08	
raw	Occupation, permanent crop, vine, intensive	m^2a	1		1.3E-08	
raw	Occupation, sea and ocean	m^2a				
raw	Occupation, shrub land, sclerophyllous	m^2a	1		1.6E-08	
raw	Occupation, traffic area	m^2a		1		2.1E-08
raw	Occupation, traffic area, rail embankment	m^2a		1		2.1E-08
raw	Occupation, traffic area, rail network	m^2a		1		2.1E-08
raw	Occupation, traffic area, road embankment	m^2a		1		2.1E-08
raw	Occupation, traffic area, road network	m^2a		1		2.1E-08
raw	Occupation, tropical rain forest	m^2a	1		9.3E-09	
raw	Occupation, unknown	m^2a	0.4	0.6	1.6E-08	1.6E-08
raw	Occupation, urban, continuously built	m^2a		1		2.1E-08

Table C.9 Characterization factor of land occupation (ALOP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)		Endpoint(H)	
			Agricultural land occupation m^2a	Urban land occupation m^2a	Agricultural land occupation EQ(species.yr)	Urban land occupation EQ(species.yr)
raw	Occupation, urban, discontinuously built	m^2a		1		2.1E-08
raw	Occupation, urban, green areas	m^2a		1		2.1E-08
raw	Occupation, water bodies, artificial	m^2a				
raw	Occupation, water courses, artificial	m^2a				

Table C.10 Characterization factor of natural land transformation (LTP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, to forest	m^2	-1	-1.9E-06
raw	Transformation, to forest, extensive	m^2	-1	-1.9E-06
raw	Transformation, to forest, intensive	m^2	-1	-1.9E-06
raw	Transformation, to forest, intensive, clear-cutting	m^2	-1	-1.9E-06
raw	Transformation, to forest, intensive, normal	m^2	-1	-1.9E-06
raw	Transformation, to forest, intensive, short-cycle	m^2	-1	-1.9E-06
raw	Transformation, to sea and ocean	m^2	-1	0.0E+00

Table C.10 Characterization factor of natural land transformation (LTP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, to tropical rain forest	m^2	-1	-6.3E-05
raw	Transformation, to unknown	m^2	-0.4	-7.5E-07
raw	Transformation, from unknown	m^2	0.4	7.5E-07
raw	Transformation, from forest	m^2	1	1.9E-06
raw	Transformation, from forest, extensive	m^2	1	1.9E-06
raw	Transformation, from forest, intensive	m^2	1	1.9E-06
raw	Transformation, from forest, intensive, clear-cutting	m^2	1	1.9E-06
raw	Transformation, from forest, intensive, normal	m^2	1	1.9E-06
raw	Transformation, from forest, intensive, short-cycle	m^2	1	1.9E-06
raw	Transformation, from sea and ocean	m^2	1	0.0E+00
raw	Transformation, from tropical rain forest	m^2	1	6.3E-05
raw	Transformation, from arable	m^2		
raw	Transformation, from arable, non-irrigated	m^2		
raw	Transformation, from arable, non-irrigated, diverse-intensive	m^2		
raw	Transformation, from arable, non-irrigated, fallow	m^2		

Table C.10 Characterization factor of natural land transformation (LTP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, from arable, non-irrigated, fallow	m^2		
raw	Transformation, from arable, non-irrigated, monotone-intensive	m^2		
raw	Transformation, from dump site	m^2		
raw	Transformation, from dump site, benthos	m^2		
raw	Transformation, from dump site, inert material landfill	m^2		
raw	Transformation, from dump site, residual material landfill	m^2		
raw	Transformation, from dump site, sanitary landfill	m^2		
raw	Transformation, from dump site, slag compartment	m^2		
raw	Transformation, from heterogeneous, agricultural	m^2		
raw	Transformation, from industrial area	m^2		
raw	Transformation, from industrial area, benthos	m^2		
raw	Transformation, from industrial area, built up	m^2		
raw	Transformation, from industrial area, vegetation	m^2		
raw	Transformation, from mineral extraction site	m^2		
raw	Transformation, from pasture and meadow	m^2		
raw	Transformation, from pasture and meadow, extensive	m^2		

Table C.10 Characterization factor of natural land transformation (LTP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, from pasture and meadow, intensive	m^2		
raw	Transformation, from permanent crop	m^2		
raw	Transformation, from permanent crop, fruit	m^2		
raw	Transformation, from permanent crop, fruit, extensive	m^2		
raw	Transformation, from permanent crop, fruit, intensive	m^2		
raw	Transformation, from permanent crop, vine	m^2		
raw	Transformation, from permanent crop, vine, extensive	m^2		
raw	Transformation, from permanent crop, vine, intensive	m^2		
raw	Transformation, from shrub land, sclerophyllous	m^2		
raw	Transformation, from traffic area, rail embankment	m^2		
raw	Transformation, from traffic area, rail network	m^2		
raw	Transformation, from traffic area, road embankment	m^2		
raw	Transformation, from traffic area, road network	m^2		
raw	Transformation, from urban, continuously built	m^2		
raw	Transformation, from urban, discontinuously built	m^2		
raw	Transformation, from water bodies, artificial	m^2		
raw	Transformation, from water courses, artificial	m^2		

Table C.10 Characterization factor of natural land transformation (LTP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, to arable	m^2		
raw	Transformation, to arable, non-irrigated	m^2		
raw	Transformation, to arable, non-irrigated, diverse-intensive	m^2		
raw	Transformation, to arable, non-irrigated, fallow	m^2		
raw	Transformation, to arable, non-irrigated, monotone-intensive	m^2		
raw	Transformation, to arable, organic	m^2		
raw	Transformation, to dump site	m^2		
raw	Transformation, to dump site, benthos	m^2		
raw	Transformation, to dump site, inert material landfill	m^2		
raw	Transformation, to dump site, residual material landfill	m^2		
raw	Transformation, to dump site, sanitary landfill	m^2		
raw	Transformation, to dump site, slag compartment	m^2		
raw	Transformation, to heterogeneous, agricultural	m^2		
raw	Transformation, to industrial area	m^2		
raw	Transformation, to industrial area, benthos	m^2		
raw	Transformation, to industrial area, built up	m^2		
raw	Transformation, to industrial area, vegetation	m^2		

Table C.10 Characterization factor of natural land transformation (LTP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, to mineral extraction site	m^2		
raw	Transformation, to pasture and meadow	m^2		
raw	Transformation, to pasture and meadow, extensive	m^2		
raw	Transformation, to pasture and meadow, intensive	m^2		
raw	Transformation, to pasture and meadow, organic	m^2		
raw	Transformation, to permanent crop	m^2		
raw	Transformation, to permanent crop, fruit	m^2		
raw	Transformation, to permanent crop, fruit, extensive	m^2		
raw	Transformation, to permanent crop, fruit, intensive	m^2		
raw	Transformation, to permanent crop, vine	m^2		
raw	Transformation, to permanent crop, vine, extensive	m^2		
raw	Transformation, to permanent crop, vine, intensive	m^2		
raw	Transformation, to shrub land, sclerophyllous	m^2		
raw	Transformation, to traffic area, rail embankment	m^2		
raw	Transformation, to traffic area, rail network	m^2		
raw	Transformation, to traffic area, road embankment	m^2		

Table C.10 Characterization factor of natural land transformation (LTP 100) (cont.)

Compartment	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpojnt (Ecosystems)(H)
			m^2	species.yr
raw	Transformation, to traffic area, road network	m^2		
raw	Transformation, to urban, continuously built	m^2		
raw	Transformation, to urban, discontinuously built	m^2		
raw	Transformation, to water bodies, artificial	m^2		
raw	Transformation, to water courses, artificial	m^2		

Table C.11 Characterization factor of natural water depletion (WDP 100)

Compartment	Substance name (ReCiPe)	Unit	Midpoint
			m^3
raw	Water, barrage	kg	0.001
raw	Water, cooling, drinking	kg	0.001
raw	Water, cooling, surface	kg	0.001
raw	Water, cooling, unspecified natural origin/kg	kg	0.001
raw	Water, cooling, unspecified natural origin/m3	m^3	1
raw	Water, cooling, well, in ground	kg	0.001
raw	Water, fossil	m^3	1
raw	Water, fresh	m^3	1
raw	Water, groundwater consumption	kg	0.001
raw	Water, lake	m^3	1
raw	Water, process and cooling, unspecified natural origin	m^3	1
raw	Water, process, drinking	kg	0.001
raw	Water, process, surface	kg	0.001
raw	Water, process, unspecified natural origin/kg	kg	0.001
raw	Water, process, unspecified natural origin/m3	m^3	1
raw	Water, process, well, in ground	kg	0.001
raw	Water, rain	m^3	1
raw	Water, river	m^3	1
raw	Water, Surface water consumption	kg	0.001
raw	Water, thermoelectric groundwater consumption	kg	0.001
raw	Water, thermoelectric surface water consumption	kg	0.001
raw	Water, turbine use, unspecified natural origin	m^3	1
raw	Water, unspecified natural origin/kg	kg	0.001
raw	Water, unspecified natural origin/m3	m^3	1
raw	Water, well, in ground	m^3	1

Table C.12 Characterization factor of natural metal depletion (MDP 100)

Compartments	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg Fe eq	RA($)
raw	Ag	kg	286.12	20.46
raw	Al	kg	0.09	0.01
raw	Au	kg	69940.31	5000.73
raw	Co	kg	1.01	0.07
raw	Cr	kg	24.93	1.78
raw	Cu	kg	42.69	3.05
raw	Fe	kg	1.00	0.07
raw	Ir	kg	92.48	6.61
raw	Mn	kg	76.61	5.48
raw	Mo	kg	207.51	14.84
raw	Ni	kg	12.53	0.90
raw	Os	kg	6484.63	463.65
raw	Pb	kg	1.77	0.13
raw	Pd	kg	3812.28	272.58
raw	Pt	kg	162805.20	11640.57
raw	Rh	kg	20328.19	1453.47
raw	Ru	kg	2007.66	143.55
raw	Sn	kg	1271.31	90.90
raw	U	kg	122.54	8.76
raw	Zn	kg	2.25	0.16
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	42.70	3.05

Table C.12 Characterization factor of natural metal depletion (MDP 100) (cont.)

Compartments	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg Fe eq	RA($)
raw		kg	42.70	3.05
raw		kg	42.70	3.05
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	69900.00	4997.85
raw		kg	1.77	0.13
raw		kg	208.00	14.87
raw		kg	208.00	14.87
raw		kg	208.00	14.87
raw		kg	208.00	14.87
raw		kg	208.00	14.87
raw		kg	208.00	14.87
raw		kg	208.00	14.87
raw		kg	12.50	0.89
raw		kg	12.50	0.89
raw		kg	12.50	0.89
raw		kg	3810.00	272.42
raw		kg	3810.00	272.42
raw		kg	163000.00	11654.50
raw		kg	163000.00	11654.50
raw		kg	20300.00	1451.45
raw		kg	20300.00	1451.45
raw		kg	286.00	20.45

Table C.12 Characterization factor of natural metal depletion (MDP 100) (cont.)

Compartments	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg Fe eq	RA($)
raw		kg	286.00	20.45
raw		kg	286.00	20.45
raw		kg	286.00	20.45
raw		kg	286.00	20.45
raw		kg	286.00	20.45
raw		kg	2.25	0.16
raw		kg	2.25	0.16
raw		kg	2.25	0.16

Table C.13 Characterization factor of fossil depletion (FDP 100)

Compartments	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg oil eq	RA($)
raw	Coal, 18 MJ per kg, in ground	kg	0.41	0.07
raw	Coal, 26.4 MJ per kg, in ground	kg	0.60	0.10
raw	Coal, 29.3 MJ per kg, in ground	kg	0.67	0.11
raw	Coal, brown, 10 MJ per kg, in ground	kg	0.23	0.04
raw	Coal, brown, 8 MJ per kg, in ground	kg	0.18	0.03
raw	Coal, brown	kg	0.22	0.04
raw	Coal, feedstock, 26.4 MJ per kg, in ground	kg	0.60	0.10
raw	Coal, hard	kg	0.43	0.07
raw	Energy, from coal	MJ	0.02	0.00

Table C.13 Characterization factor of fossil depletion (FDP 100)

Compartments	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg oil eq	RA($)
raw	Energy, from coal, brown	MJ	0.02	0.00
raw	Energy, from gas, natural	MJ	0.02	0.00
raw	Energy, from oil	MJ	0.02	0.00
raw	Energy, from peat	MJ	0.02	0.00
raw	Energy, from sulfur	MJ	0.02	0.00
raw	Gas, mine, off-gas, process, coal mining/kg	kg	1.07	0.18
raw	Gas, mine, off-gas, process, coal mining/m3	m^3	0.86	0.14
raw	Gas, natural, 30.3 MJ per kg, in ground	kg	0.72	0.12
raw	Gas, natural, 35 MJ per m3, in ground	m^3	0.84	0.14
raw	Gas, natural, 36.6 MJ per m3, in ground	m^3	0.87	0.14
raw	Gas, natural, 46.8 MJ per kg, in ground	kg	1.11	0.18
raw	Gas, natural, feedstock, 35 MJ per m3, in ground	m^3	0.84	0.14
raw	Gas, natural, feedstock, 46.8 MJ per kg, in ground	kg	1.11	0.18
raw	Gas, natural	m^3	0.82	0.14
raw	Gas, off-gas, oil production, in ground	m^3	0.86	0.14
raw	Gas, petroleum, 35 MJ per m3, in ground	m^3	0.84	0.14
raw	Methane	kg	1.19	0.20

Table C.13 Characterization factor of fossil depletion (FDP 100) (cont.)

Compartments	Substance name (ReCiPe)	Unit	Midpoint(H)	Endpoint(H)
			kg oil eq	RA($)
raw	Oil, crude, 38400 MJ per m3, in ground	m^3	916.88	151.71
raw	Oil, crude, 41 MJ per kg, in ground	kg	0.98	0.16
raw	Oil, crude, 42 MJ per kg, in ground	kg	1.00	0.17
raw	Oil, crude, 42.6 MJ per kg, in ground	kg	1.01	0.17
raw	Oil, crude, 42.7 MJ per kg, in ground	kg	1.02	0.17
raw	Oil, crude, feedstock, 41 MJ per kg, in ground	kg	0.98	0.16
raw	Oil, crude, feedstock, 42 MJ per kg, in ground	kg	1.00	0.17
raw	Oil, crude	kg	1.04	0.17

Table C.14 Normalization factor of ReCiPe2008

Impact	Impact category	Unit	Europe			World		
			(I)	**(H)**	**(E)**	**(I)**	**(H)**	**(E)**
Midpoint	Climate change	kg CO_2 eq/p/yr	1.41E+04	1.12E+04	9.66E+03	9.49E+03	6.89E+03	5.53E+03
	Ozone depletion	kg CFC-11 eq/p/yr	2.20E-02	2.20E-02	2.20E-02	3.76E-02	3.76E-02	3.76E-02
	terrestrial acidification	kg SO_2 eq/p/yr	3.23E+01	3.44E+01	3.84E+01	3.57E+01	3.82E+01	4.21E+01
	freshwater eutrophication	kg P eq/p/yr	4.15E-01	4.15E-01	4.15E-01	2.90E-01	2.90E-01	2.90E-01
	marine eutrophication	kg N eq/p/yr	1.01E+01	1.01E+01	1.01E+01	7.34E+00	7.34E+00	7.34E+00
	human toxicity	kg 1,4-DB eq/p/yr	3.49E+02	6.27E+02	4.47E+03	2.12E+02	3.26E+02	1.45E+03
	photochemical oxidant formation	kg NMVOC/p/yr	5.68E+01	5.68E+01	5.68E+01	5.67E+01	5.67E+01	5.67E+01
	particulate matter formation	kg PM10 eq/p/yr	1.49E+01	1.49E+01	1.49E+01	1.41E+01	1.41E+01	1.41E+01
	terrestrial ecotoxicity	kg 1,4-DB eq/p/yr	8.23E+00	8.25E+00	1.40E+01	5.92E+00	5.93E+00	8.15E+00
	freshwater ecotoxicity	kg 1,4-DB eq/p/yr	1.10E+01	1.10E+01	1.17E+01	4.30E+00	4.30E+00	4.55E+00
	marine ecotoxicity	kg 1,4-DB eq/p/yr	7.61E+00	8.73E+00	2.53E+03	2.10E+00	2.46E+00	6.76E+02
	ionising radiation	kg U^{235} eq/p/yr	2.06E+03	6.26E+03	6.26E+03	4.33E+02	1.32E+03	1.32E+03
	agricultural land occupation	m^2a/p/yr	4.52E+03	4.52E+03	4.52E+03	5.42E+03	5.42E+03	5.42E+03
	urban land occupation	m^2a/p/yr	4.07E+02	4.07E+02	4.07E+02	7.75E+02	7.75E+02	7.75E+02
	natural land transformation	m^2/p/yr	1.61E-01	1.61E-01	1.61E-01	1.20E+01	1.20E+01	1.20E+01
	water depletion	m^3/p/yr	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table C.14 Normalization factor of ReCiPe2008 (cont.)

Impact	Impact category	Unit	Europe			World		
			(I)	(H)	(E)	(I)	(H)	(E)
	metal depletion	kg Fe eq/yr	7.13E+02	7.13E+02	7.13E+02	4.45E+02	4.45E+02	4.45E+02
	fossil depletion	kg oil eq/p/yr	1.56E+03	1.56E+03	1.56E+03	1.29E+03	1.29E+03	1.29E+03
Endpoint	Ecosystems	species.yr/p/yr	1.86E-04	1.81E-04	2.75E-04	8.00E-04	9.17E-04	2.48E-03
	Human health	DALY/p/yr	2.10E-02	2.02E-02	4.11E-02	1.51E-02	1.36E-02	2.42E-02
	Resources	$/p/yr	1.31E+02	3.08E+02	3.08E+02	9.85E+01	2.45E+02	2.45E+02

Table C.15 Weighting factor of ReCiPe2008

Perspective:	Ecosystems	Human health	Resources	Total
Average	400	400	200	1000
Individualist	250	550	200	1000
Hierarchist	400	300	300	1000
Egalitarian	500	300	200	1000

Midpoint impact	Unit	Human health (DALY)			Ecosystems (species.yr)			Resources ($)		
		HH_I	HH_H	HH_E	ED_I	ED_H	ED_E	RA_I	RA_H	RA_E
CC	kg CO_2 eq	1.19E-06	1.40E-06	3.51E-06	7.93E-09	7.93E-09	1.87E-08			
OD	kg CFC-11 eq	/	/	/						
TA	kg SO_2 eq				1.52E-09	5.80E-09	1.42E-08			
FE	kg P eq				4.44E-08	4.44E-08	4.44E-08			
HT	kg 1,4-DB eq	7.00E-07	7.00E-07	7.00E-07						
POF	kg NMVOC	3.90E-08	3.90E-08	3.90E-08						
PMF	kg PM_{10} eq	2.60E-04	2.60E-04	2.60E-04						
TET	kg 1,4-DB eq				1.51E-07	1.51E-07	1.51E-07			
FET	kg 1,4-DB eq				8.61E-10	8.61E-10	8.61E-10			
MET	kg 1,4-DB eq				1.76E-10	1.76E-10	1.76E-10			
IR	kg U^{235} eq	1.64E-08	1.64E-08	1.64E-08						
ALO	m^2a				/	/	/			
ULO	m^2a				/	/	/			
NLT	m^2				/	/	/			
FRD	kg oil eq							5.17E-02	1.65E-01	1.65E-01
MRD	kg Fe eq							7.15E-02	7.15E-02	7.15E-02

APPENDIX D

Appendix D-1 SimaPro data for Production of plastic drum formula-1

SimaPro 8.0.5.13	Impact assessment
Project	LCA of Plastic drum
Calculation:	Analyze
Results:	Impact assessment
Product:	1 p HDPE plastic drum - Senerio 1
Method:	ReCiPe Midpoint (H) V1.12 / Europe Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Table D.1 SimaPro data for Production of plastic drum formula-1

Impact category	Unit	Total	Scenario 1	Collection process	Washing process	Postconsumer waste
Climate change	kg CO_2 eq	1.10E+01	8.82E+00	6.57E-01	1.01E+00	5.60E-01
Ozone depletion	kg CFC-11 eq	5.02E-09	0.00E+00	0.00E+00	2.72E-10	4.75E-09
Terrestrial acidification	kg SO_2 eq	1.83E-02	1.78E-02	0.00E+00	6.07E-05	4.34E-04
Freshwater eutrophication	kg P eq	2.02E-04	0.00E+00	0.00E+00	4.74E-08	2.02E-04
Marine eutrophication	kg N eq	3.95E-04	2.98E-04	0.00E+00	2.23E-06	9.44E-05
Human toxicity	kg 1,4-DB eq	1.42E-03	9.64E-05	0.00E+00	2.37E-04	1.09E-03
Photochemical oxidant formation	kg NMVOC	9.25E-03	8.56E-03	1.03E-05	7.52E-05	6.04E-04
Particulate matter formation	kg PM_{10} eq	5.12E-03	4.37E-03	0.00E+00	1.87E-05	7.30E-04
Terrestrial ecotoxicity	kg 1,4-DB eq	3.79E-06	1.37E-07	0.00E+00	7.17E-08	3.58E-06
Freshwater ecotoxicity	kg 1,4-DB eq	2.99E-05	1.48E-05	0.00E+00	2.56E-06	1.25E-05
Marine ecotoxicity	kg 1,4-DB eq	3.44E-05	1.54E-05	0.00E+00	2.54E-06	1.64E-05
Ionising radiation	kBq U^{235} eq	6.06E-03	0.00E+00	0.00E+00	3.15E-04	5.75E-03
Agricultural land occupation	m^2a	7.68E-06	0.00E+00	0.00E+00	7.68E-06	0.00E+00
Urban land occupation	m^2a	1.60E-06	0.00E+00	0.00E+00	1.60E-06	0.00E+00
Natural land transformation	m^2	2.28E-08	0.00E+00	0.00E+00	2.28E-08	0.00E+00
Water depletion	m^3	1.54E-02	1.45E-02	0.00E+00	6.07E-04	2.69E-04
Metal depletion	kg Fe eq	2.80E-03	6.49E-04	0.00E+00	2.64E-05	2.12E-03
Fossil depletion	kg oil eq	5.77E+00	5.11E+00	2.38E-01	3.82E-01	3.58E-02

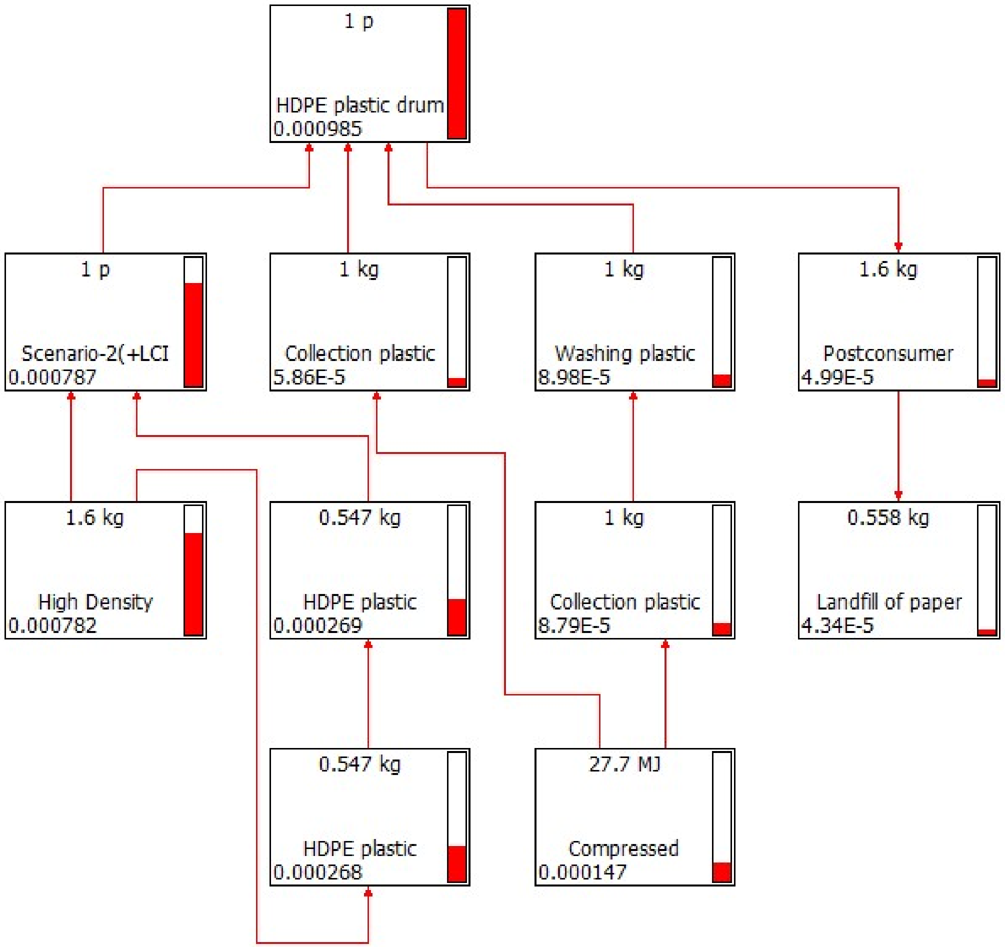

Figure D-1 Impact assessment at midpoint level of plastic production Formula-1

Appendix D-2 SimaPro data for Production of plastic drum formula-2

SimaPro 8.0.5.13	Impact assessment
Project	LCA of Plastic drum
Calculation:	Analyze
Results:	Impact assessment
Product:	1 p HDPE plastic drum - Senerio 2
	ReCiPe Midpoint (H) V1.12 / Europe
Method:	Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Table D2 SimaPro data for Production of plastic drum formula-2

Impact category	Unit	Total	Scenario 2	Collection process	Washing process	Postconsumer waste
Climate change	kg CO_2 eq	1.07E+01	8.11E+00	9.86E-01	1.01E+00	5.60E-01
Ozone depletion	kg CFC-11 eq	5.10E-09	7.43E-11	0.00E+00	2.72E-10	4.75E-09
Terrestrial acidification	kg SO_2 eq	1.75E-02	1.70E-02	0.00E+00	6.07E-05	4.34E-04
Freshwater eutrophication	kg P eq	2.02E-04	1.25E-08	0.00E+00	4.74E-08	2.02E-04
Marine eutrophication	kg N eq	6.24E-04	5.27E-04	0.00E+00	2.23E-06	9.44E-05
Human toxicity	kg 1,4-DB eq	2.41E-03	1.09E-03	0.00E+00	2.37E-04	1.09E-03
Photochemical oxidant formation	kg NMVOC	1.66E-02	1.59E-02	1.54E-05	7.52E-05	6.04E-04
Particulate matter formation	kg PM_{10} eq	5.59E-03	4.84E-03	0.00E+00	1.87E-05	7.30E-04
Terrestrial ecotoxicity	kg 1,4-DB eq	4.62E-05	4.26E-05	0.00E+00	7.17E-08	3.58E-06
Freshwater ecotoxicity	kg 1,4-DB eq	3.12E-05	1.61E-05	0.00E+00	2.56E-06	1.25E-05
Marine ecotoxicity	kg 1,4-DB eq	3.74E-04	3.55E-04	0.00E+00	2.54E-06	1.64E-05
Ionising radiation	kBq U^{235} eq	6.15E-03	8.61E-05	0.00E+00	3.15E-04	5.75E-03
Agricultural land occupation	m^2a	9.70E-06	2.02E-06	0.00E+00	7.68E-06	0.00E+00
Urban land occupation	m^2a	2.02E-06	4.21E-07	0.00E+00	1.60E-06	0.00E+00
Natural land transformation	m^2	2.89E-08	6.02E-09	0.00E+00	2.28E-08	0.00E+00
Water depletion	m^3	1.43E-02	1.34E-02	0.00E+00	6.07E-04	2.69E-04
Metal depletion	kg Fe eq	2.58E-03	4.37E-04	0.00E+00	2.64E-05	2.12E-03
Fossil depletion	kg oil eq	4.42E+00	3.64E+00	3.57E-01	3.82E-01	3.58E-02

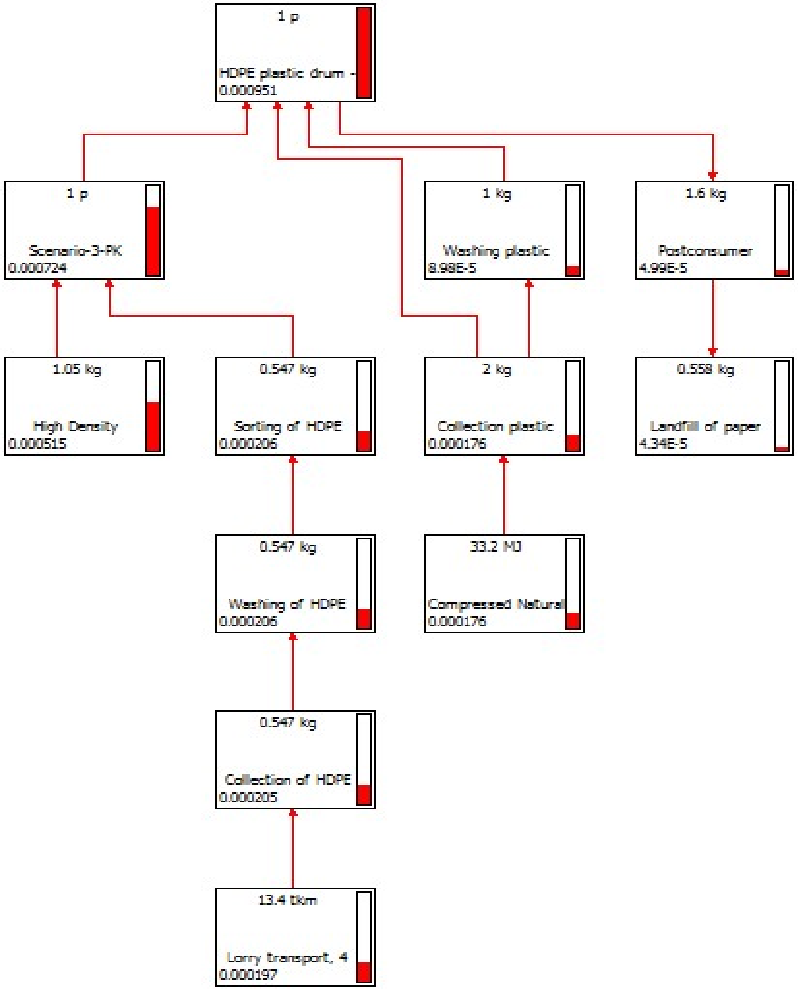

Figure D-2 Impact assessment at midpoint level of plastic production Formula-2

Appendix D-3 SimaPro data for Collection process

SimaPro 8.0.5.13	Impact assessment
Project	LCA of Plastic drum
Calculation:	Analyze
Results:	Impact assessment
Product:	1 kg Collection of HDPE plastic drum
	ReCiPe Midpoint (H) V1.12 / Europe
Method:	Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Table D.3 SimaPro data for Collection process

Impact category	Unit	Total	Collection of HDPE plastic drum	Lorry transport, 6 wheels	Liquefied petroleum gas	Lorry transport, 4 wheels	Liquefied petroleum gas
Climate change	kg CO_2 eq	4.20E+00	0.00E+00	1.98E-02	1.82E-02	4.04E+00	1.22E-01
Ozone depletion	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Terrestrial acidification	kg SO_2 eq	9.55E-03	0.00E+00	4.83E-05	2.34E-06	9.49E-03	1.57E-05
Freshwater eutrophication	kg P eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Marine eutrophication	kg N eq	6.02E-04	0.00E+00	3.07E-06	1.40E-07	5.98E-04	9.42E-07
Human toxicity	kg 1,4-DB eq	1.75E-03	0.00E+00	6.62E-06	4.45E-09	1.75E-03	2.99E-08
Photochemical oxidant formation	kg NMVOC	1.88E-02	0.00E+00	1.10E-04	4.62E-06	1.86E-02	3.10E-05
Particulate matter formation	kg PM_{10} eq	3.58E-03	0.00E+00	1.82E-05	8.57E-07	3.55E-03	5.76E-06
Terrestrial ecotoxicity	kg 1,4-DB eq	7.76E-05	0.00E+00	3.61E-07	1.00E-13	7.72E-05	6.74E-13
Freshwater ecotoxicity	kg 1,4-DB eq	1.04E-05	0.00E+00	4.84E-08	1.51E-11	1.03E-05	1.02E-10
Marine ecotoxicity	kg 1,4-DB eq	6.29E-04	0.00E+00	2.93E-06	1.23E-11	6.27E-04	8.28E-11
Ionising radiation	kBq U^{235} eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Agricultural land occupation	m^2a	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Urban land occupation	m^2a	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	m^2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water depletion	m^3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Metal depletion	kg Fe eq	2.54E-07	0.00E+00	0.00E+00	3.29E-08	0.00E+00	2.21E-07
Fossil depletion	kg oil eq	4.83E-01	0.00E+00	0.00E+00	6.26E-02	0.00E+00	4.21E-01

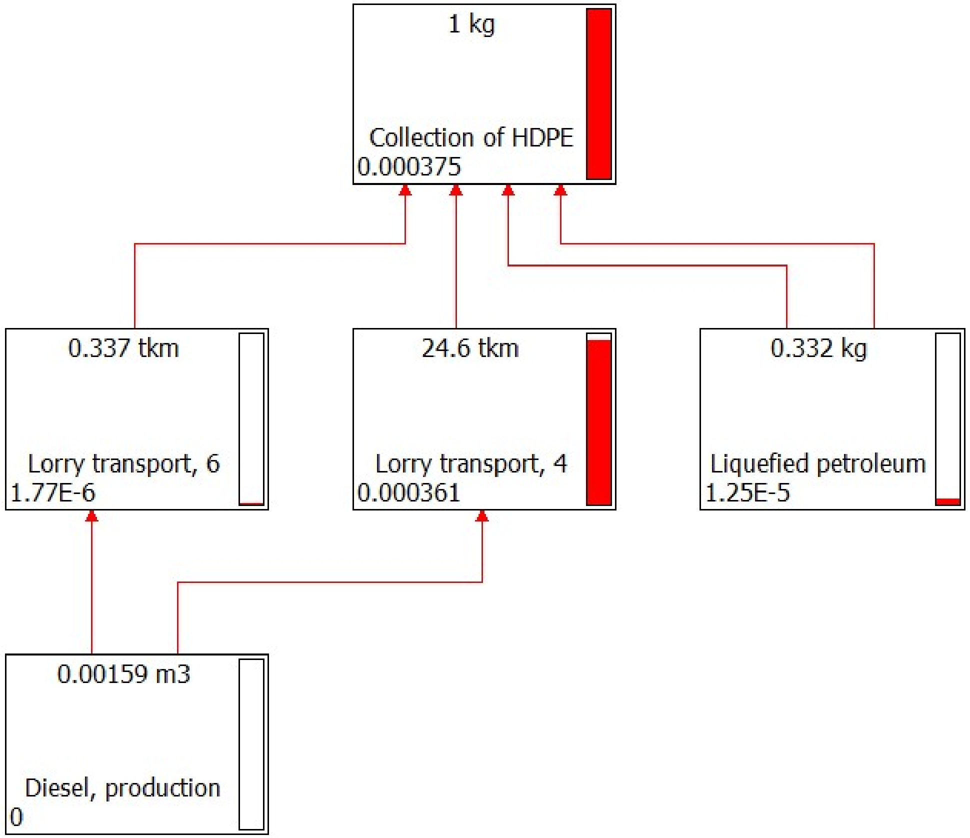

Figure D-3 Impact assessment at midpoint level of collection process

Appendix D-4 SimaPro data for washing process

SimaPro 8.0.5.13	Impact assessment
Project	LCA of Plastic drum
Calculation:	Analyze
Results:	Impact assessment
Product:	1 kg Washing of HDPE plastic drum
Method:	ReCiPe Midpoint (H) V1.12 / Europe Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Table D.4 SimaPro data for washing process

Impact category	Unit	Total	Washing of HDPE plastic drum	Collection of HDPE plastic drum	Sodium hydroxide (50% NaOH)	Alkylbenzene sulfonate	Electricity	Tap water
Climate change	kg CO_2 eq	4.78E+00	0.00E+00	4.75E+00	1.94E-03	2.19E-04	9.32E-03	1.96E-02
Ozone depletion	kg CFC-11 eq	4.08E-10	0.00E+00	0.00E+00	3.79E-10	2.94E-11	0.00E+00	0.00E+00
Terrestrial acidification	kg SO_2 eq	1.09E-02	0.00E+00	1.08E-02	1.25E-05	1.29E-06	1.10E-05	6.61E-05
Freshwater eutrophication	kg P eq	6.87E-08	0.00E+00	0.00E+00	4.52E-09	6.41E-08	0.00E+00	0.00E+00
Marine eutrophication	kg N eq	6.83E-04	0.00E+00	6.80E-04	1.65E-07	1.47E-07	4.87E-07	2.54E-06
Human toxicity	kg 1,4-DB eq	2.33E-03	0.00E+00	1.98E-03	2.45E-04	9.81E-05	2.42E-08	8.53E-06
Photochemical oxidant formation	kg NMVOC	2.13E-02	0.00E+00	2.12E-02	4.89E-06	1.02E-06	1.28E-05	7.08E-05
Particulate matter formation	kg PM_{10} eq	4.07E-03	0.00E+00	4.04E-03	3.91E-06	4.98E-07	3.56E-06	2.01E-05

Table D.4 SimaPro data for washing process (cont.)

Impact category	Unit	Total	Washing of HDPE plastic drum	Collection of HDPE plastic drum	Sodium hydroxide (50% NaOH)	Alkylbenzene sulfonate	Electricity	Tap water
Terrestrial ecotoxicity	kg 1,4-DB eq	8.77E-05	0.00E+00	8.76E-05	8.68E-08	2.00E-08	9.38E-14	3.73E-11
Freshwater ecotoxicity	kg 1,4-DB eq	1.54E-05	0.00E+00	1.17E-05	6.33E-07	3.07E-06	3.69E-11	1.27E-08
Marine ecotoxicity	kg 1,4-DB eq	7.14E-04	0.00E+00	7.11E-04	7.92E-07	2.91E-06	3.32E-11	1.15E-08
Ionising radiation	kBq U^{235} eq	4.73E-04	0.00E+00	0.00E+00	4.58E-04	1.43E-05	0.00E+00	0.00E+00
Agricultural land occupation	m^2a	1.11E-05	0.00E+00	0.00E+00	0.00E+00	1.11E-05	0.00E+00	0.00E+00
Urban land occupation	m^2a	2.31E-06	0.00E+00	0.00E+00	0.00E+00	2.31E-06	0.00E+00	0.00E+00
Natural land transformation	m^2	3.30E-08	0.00E+00	0.00E+00	0.00E+00	3.30E-08	0.00E+00	0.00E+00
Water depletion	m^3	9.10E-04	-2.78E-02	0.00E+00	9.72E-06	2.71E-06	0.00E+00	2.87E-02
Metal depletion	kg Fe eq	3.93E-05	0.00E+00	2.87E-07	7.31E-07	1.57E-05	1.28E-06	2.14E-05
Fossil depletion	kg oil eq	5.83E-01	0.00E+00	5.46E-01	4.54E-04	1.65E-04	2.96E-03	3.40E-02

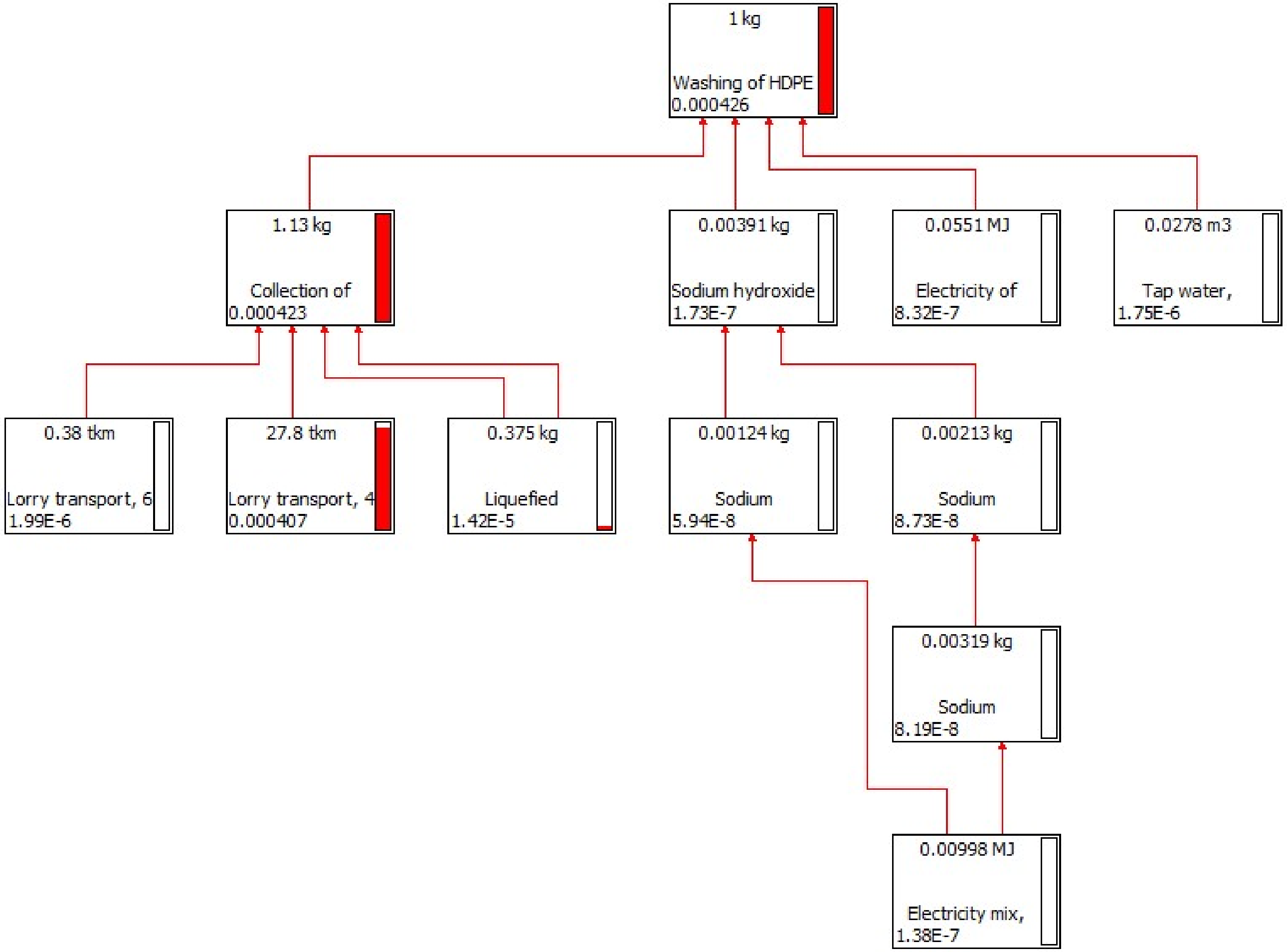

Figure D-4 Impact assessment at midpoint level of washing process

Appendix D-5 SimaPro data for Inline recycle production process

SimaPro 8.0.5.13	Impact assessment
Project	LCA of Plastic drum
Calculation:	Analyze
Results:	Impact assessment
Product:	1 kg HDPE plastic pellet(Virgin+LCI waste) (of project LCA of Plastic drum)
Method:	ReCiPe Midpoint (H) V1.12 / Europe Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Table D.5 SimaPro data for Inline recycle production process

Impact category	Unit	Total	HDPE plastic pellet	HDPE plastic flake	Electricity
Climate change	kg CO_2 eq	8.01E+00	0.00E+00	8.00E+00	8.78E-03
Ozone depletion	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Terrestrial acidification	kg SO_2 eq	1.62E-02	0.00E+00	1.62E-02	1.04E-05
Freshwater eutrophication	kg P eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Marine eutrophication	kg N eq	2.70E-04	0.00E+00	2.70E-04	4.59E-07
Human toxicity	kg 1,4-DB eq	7.94E-05	0.00E+00	7.93E-05	2.28E-08
Photochemical oxidant formation	kg NMVOC	7.74E-03	0.00E+00	7.73E-03	1.21E-05
Climate change	kg CO_2 eq	8.01E+00	0.00E+00	8.00E+00	8.78E-03
Ozone depletion	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Terrestrial acidification	kg SO_2 eq	1.62E-02	0.00E+00	1.62E-02	1.04E-05
Freshwater eutrophication	kg P eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Marine eutrophication	kg N eq	2.70E-04	0.00E+00	2.70E-04	4.59E-07
Human toxicity	kg 1,4-DB eq	7.94E-05	0.00E+00	7.93E-05	2.28E-08
Photochemical oxidant formation	kg NMVOC	7.74E-03	0.00E+00	7.73E-03	1.21E-05
Particulate matter formation	kg PM10 eq	3.96E-03	0.00E+00	3.96E-03	3.35E-06
Terrestrial ecotoxicity	kg 1,4-DB eq	7.80E-10	0.00E+00	7.79E-10	8.84E-14

Table D.5 SimaPro data for Inline recycle production process (cont.)

Impact category	Unit	Total	HDPE plastic pellet	HDPE plastic flake	Electricity
Freshwater ecotoxicity	kg 1,4-DB eq	1.34E-05	0.00E+00	1.34E-05	3.48E-11
Marine ecotoxicity	kg 1,4-DB eq	1.30E-05	0.00E+00	1.30E-05	3.13E-11
Ionising radiation	kBq U^{235} eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Agricultural land occupation	m^2a	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Urban land occupation	m^2a	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	m^2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water depletion	m^3	1.20E-02	0.00E+00	1.20E-02	0.00E+00
Metal depletion	kg Fe eq	5.89E-04	0.00E+00	5.88E-04	1.20E-06
Fossil depletion	kg oil eq	4.65E+00	0.00E+00	4.64E+00	2.79E-03

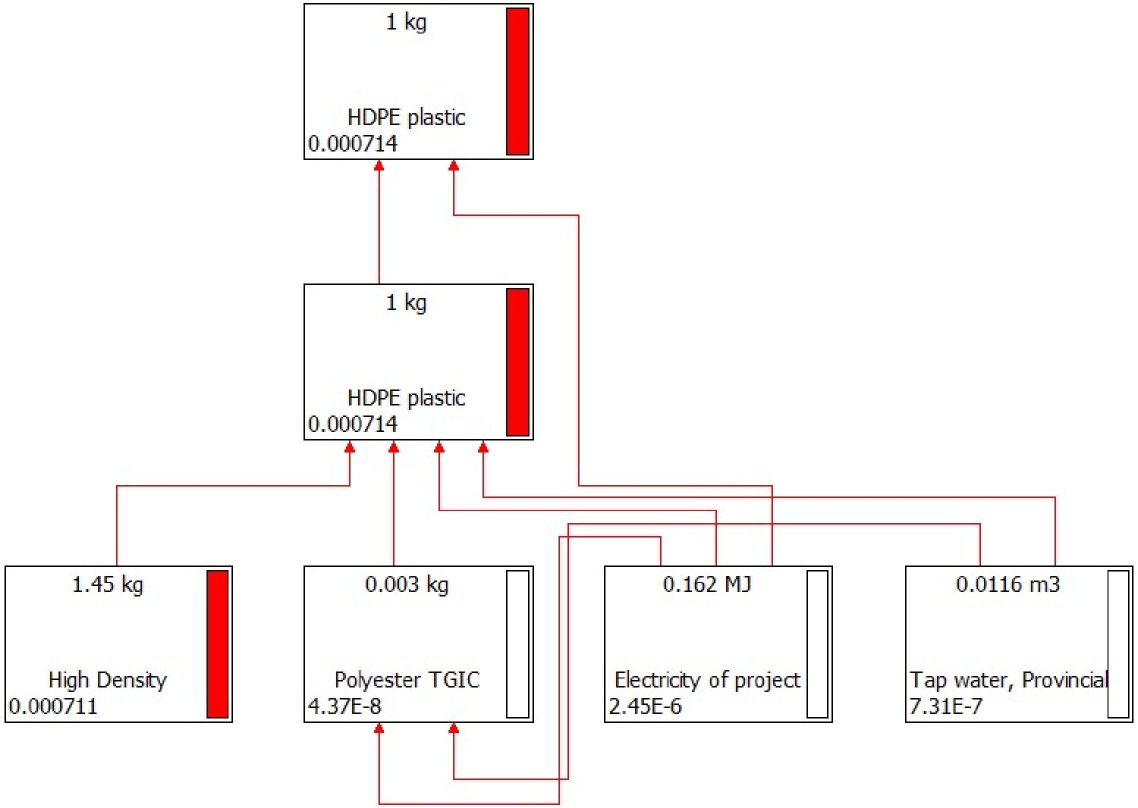

Figure D-5 Impact assessment at midpoint level of Inline recycle pellets production

Appendix D-6 SimaPro data for Outline recycle production process

SimaPro 8.0.5.13	Impact assessment
Project	LCA of Plastic drum
Calculation:	Analyze
Results:	Impact assessment
Product:	1 kg Sorting of HDPE plastic drum
Method:	ReCiPe Midpoint (H) V1.12 / Europe Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Table D.6 SimaPro data for Outline recycle production process

Impact category	Unit	Total	Sorting of HDPE plastic drum	Plastic drum for recycle	Electricity
Climate change	kg CO_2 eq	1.35E-03	0.00E+00	0.00E+00	1.35E-03
Ozone depletion	kg CFC-11 eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Terrestrial acidification	kg SO_2 eq	1.60E-06	0.00E+00	0.00E+00	1.60E-06
Freshwater eutrophication	kg P eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Marine eutrophication	kg N eq	7.07E-08	0.00E+00	0.00E+00	7.07E-08
Human toxicity	kg 1,4-DB eq	3.52E-09	0.00E+00	0.00E+00	3.52E-09
Photochemical oxidant formation	kg NMVOC	1.86E-06	0.00E+00	0.00E+00	1.86E-06
Particulate matter formation	kg PM_{10} eq	5.17E-07	0.00E+00	0.00E+00	5.17E-07
Terrestrial ecotoxicity	kg 1,4-DB eq	1.36E-14	0.00E+00	0.00E+00	1.36E-14
Freshwater ecotoxicity	kg 1,4-DB eq	5.36E-12	0.00E+00	0.00E+00	5.36E-12
Marine ecotoxicity	kg 1,4-DB eq	4.83E-12	0.00E+00	0.00E+00	4.83E-12
Ionising radiation	kBq U^{235} eq	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Agricultural land occupation	m^2a	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Urban land occupation	m^2a	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	m^2	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Water depletion	m^3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Metal depletion	kg Fe eq	1.85E-07	0.00E+00	0.00E+00	1.85E-07
Fossil depletion	kg oil eq	4.29E-04	0.00E+00	0.00E+00	4.29E-04

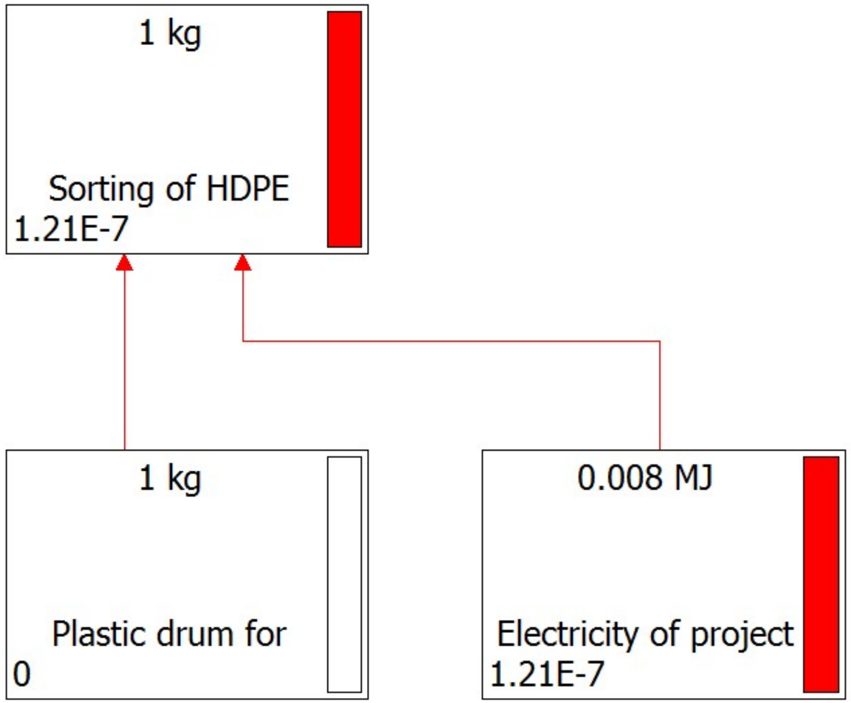

Figure D-6 Impact assessment at midpoint level of Outline recycle pellets production

APPENDIX E
LCI DATA OF DYESTUFFS

Table E.1 LCI data of dyestuff

Input	Amount	Unit	Output	Amount	Unit
Raw materials			**Product**		
Carboxyl polyester resin	5.79E-01	kg	Polyester TGIC powder coating paint	1.00E+00	kg
Triglycidyl isocyanurate (TGIC)	4.23E-02	kg	Packaging	4.00E-02	kg
BaSO4	7.27E-02	kg	**Solid waste generation**		
CaCO3	8.73E-02	kg	Contaminated raw materials packaging	9.70E-03	kg
TiO2	2.63E-01	kg	Wastes from extruder cleaning	2.05E-02	kg
Other pigments	4.00E-04	kg	Wastewater sludge	3.30E-03	kg
Benzoin	8.50E-03	kg	Off-spec. powder	1.75E-02	kg
Utilities			**Emission to water**		
Electricity	2.67E-01	kWh	Wastewater and contaminants	7.61E-04	m3
Water	7.46E-04	m3	pH	7.30E+00	
Corncob	4.15E-03	kg	Biochemical Oxygen Demand (BOD)	1.09E+01	mg

Table E.2 LCI data of dyestuff

Input	Amount	Unit	Output	Amount	Unit
Wastewater treatment substances			**Emission to water(cont.)**		
Al2(OH)5Cl			Chemical Oxygen Demand (COD)	6.61E+01	mg
Anionic polyacrylamide	1.25E-04	kg	Chloride	6.50E+02	mg

Table E.2 LCI data of dyestuff (cont.)

Input	Amount	Unit	Output	Amount	Unit
Packaging materials	2.80E-07	kg	Chlorine (Residual)	7.60E-02	mg
Polyethene film			Total Kjedahl Nitrogen (TKN)	4.29E+00	mg
Carton box	9.00E-03	kg	Cyanide	4.57E-03	mg
Plastic bag (LLDPE)	3.50E-02	kg	Fluoride ions	7.60E-02	mg
Plastic tie	4.75E-03	kg	Barium	2.00E-01	mg
	2.50E-04	kg	Total dissolved solids (TDS)	4.52E+00	mg
			Formaldehyde	1.50E-01	mg
			Phenols	1.60E-01	mg
			Grease & Oil	3.05E+00	mg
			Hydrogen sulfide	4.00E-01	mg
			Arsenic	1.52E-03	mg
			Cadmium	1.50E-02	mg
			Copper	7.60E-02	mg
			Emission to water(cont.)		
			Chromium trivalent	3.81E-03	mg
			Chromium hexavalent	3.81E-03	mg
			Iron	1.80E-01	mg
			Lead	9.90E-02	mg
			Manganese	1.90E-02	mg
			Mercury	7.61E-04	mg
			Nickel	7.60E-02	mg
			Selenium	7.61E-04	mg
			Zinc	1.30E-01	mg
			Emission to air		
			Total Suspended Particulate (TSP)	9.98E-05	kg
			Lead	1.91E-07	kg

APPENDIX F

MACHINE

Figure E-1 Production machine (66 kW)

Figure E-2 Gridding machine (15 kW)

Figure E-3 Mixing machine (7.5 kW)

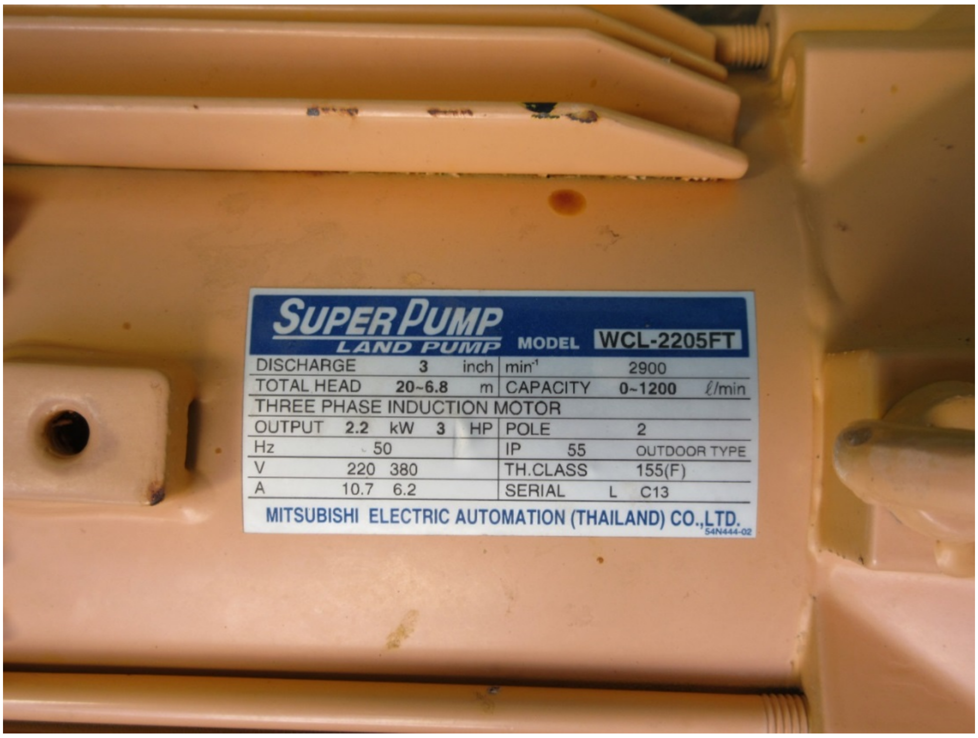

Figure E-4 Chiller machine (2.2 kW)

Figure E-5 High pressure pump (2.2 kW)

Figure E-6 Grinding machine (11 kW)

BIOGRAPHY

NAME	Mr. Kanapot Mahasaro
DATE OF BIRTH	29 August 1983
PLACE OF BIRTH	Mahasarakham, Thailand
INSTITUTION ATTENDED	Phetchaburi Rajabhat University, 2003-2007 Bachelor of Science (Chemistry) Mahidol Unvisity, 2011-2016 Master of Science(Technology of Environmental management)
HOME ADDRESS	148 Moo 4 Tabkhang, Kaoyoi, Phetchaburi Thailand 76140 Tel.099-55409838 E-mail: mahasaro_29@hotmail.com
EMPLOYMENT ADDRESS	118 Moo 4 Tabkhang, Kaoyoi, Phetchaburi Thailand 76140 Tel.099-55409838 E-mail: mahasaro_29@hotmail.com
PRESENTATION	5th International Conference on Environmental Engineering, Science and Management (May 11-13, 2016 at The Twin Tower Hotel, Bangkok, Thailand)