COMBINED LIFE CYCLE ANALYSIS AND MATERIAL FLOW ANALYSIS AS A TOOL FOR END OF LIFE OPTIONS OF USED LUBRICATING OILS

Komsan Toeipomthong

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บทคัดย่อและแฟ้มข้อมูลฉบับเต็มของวิทยานิพนธ์ตั้งแต่ปีการศึกษา 2554 ที่ให้บริการในคลังปัญญาจุฬาฯ (CUIR)
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By: Komsan Toeipomthong

Program: Petrochemical Technology

Thesis Advisors: Dr. Ampira Charoensaeng

Asst. Prof. Uthaiporn Suriyapraphadilok

Accepted by The Petroleum and Petrochemical College, Chulalongkorn University, in partial fulfilment of the requirements for the Degree of Master of Science.

.... College Dean

(Prof. Suwabun Chirachanchai)

Thesis Committee:

....

(Dr. Ampira Charoensaeng)

....

(Asst. Prof. Uthaiporn Suriyapraphadilok)

....

(Asst. Prof. Kitipat Siemanond)

....

(Assoc. Prof. Thumrongrut Mungcharoen)

ABSTRACT

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Used lubricating oils are one of the most significant material flows in the economy. After being used, they are typically contaminated with, e.g., heavy metals, which could harm the environments if they are treated improperly. The used oils should be properly treated by reprocessing or recycling which the recyled products can be used to subsitute the production the new product, as a result a net reduction of the environemental impacts. This study aimed to investigate the waste flow and then evaluate the environmental impacts of waste management options using the Material Flow Analysis (MFA, STAN v.2.6.801) and Life Cycle Assessment (LCA, SimaPro v.8.3.0) as an assessment tool. The functional unit was set as a ton of market demand of petroleum products in Thailand in the calendar year 2017. Five scenarios of waste management were developed into base case or current operation (Option 1), zero-production (Option 2), distillation (Option 3), re-refining by KTI process (Option 4) and re-refining by Revivoil process (Option 5). The MFA results shows that the secondary products obtained from waste treatment method were mainly composed of diesel (68%) followed by asphalt (20%). The LCA results show the emission hotspots of environmental impacts in each waste treatment scenario that KTI process had the least value of global warming potential impact (-1,356 kg CO_2 eq), followed by Revivoil process (-733 kg CO_2 eq), whereas the impact value of the base case was approximately 24 times higher than that of KTI process - which has the least impact option. Therefore, for sustainably used oil management, KTI process is an appropriate technology rather than the current operation.

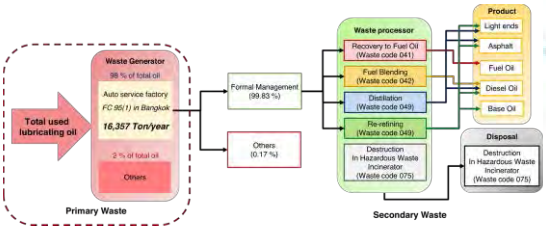
บทคัดย่อ

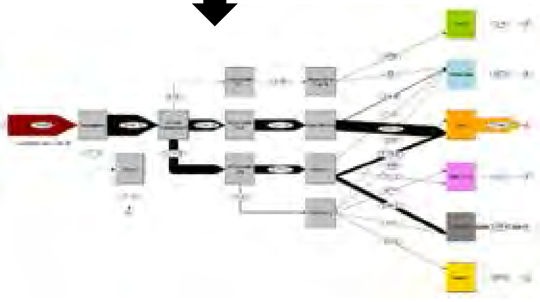
คมสัน เตยพรมทอง : การประเมินวัฏจักรชีวิตร่วมกับทฤษฎีวิเคราะห์การไหลของสารเพื่อเป็นเครื่องมือทางเลือกของกระบวนการสุดท้ายของน้ำมันหล่อลื่นที่ใช้แล้ว (Combined Life Cycle Analysis and Material Flow Analysis as a Tool for End of Life Options of Used Lubricating Oils) อ. ที่ปรึกษา : ดร. อัมพิรา เจริญแสง และ ผศ. ดร. อุทัยพร สุริยประภาดิลก 124 หน้า

น้ำมันหล่อลื่นที่ใช้แล้วเป็นวัสดุชนิดหนึ่งที่สำคัญมากที่สุดในทางเศรษฐกิจ หลังจากน้ำมันหล่อลื่นถูกใช้แล้ว โดยทั่วไปน้ำมันดังกล่าวปนเปื้อนไปด้วยสิ่งเจือปน เช่น โลหะหนัก ซึ่งอาจส่งผลกระทบต่อสิ่งแวดล้อม หากน้ำมันดังกล่าวถูกกำจัดอย่างไม่ถูกต้อง ดังนั้นน้ำมันที่ใช้แล้วจึงควรถูกบำบัดด้วยวิธีการผ่านกระบวนการซ้ำ หรือ วิธีการหมุนเวียนกลับมาใช้ใหม่ให้กลายเป็นผลิตภัณฑ์ทุติยภูมิเพื่อที่จะช่วยลดปัญหาสิ่งแวดล้อม การศึกษานี้มีวัตถุประสงค์เพื่อประเมินผลกระทบต่อสิ่งแวดล้อมของแนวทางการจัดการของเสีย โดยใช้การวิเคราะห์การไหลของวัสดุ (Material Flow Analysis: MFA, STAN v.2.6.801) และการประเมินวัฏจักรชีวิต (Life Cycle Assessment: LCA, SimaPro v.8.3.0) เพื่อใช้เป็นเครื่องมือในการประเมินผลกระทบต่อสิ่งแวดล้อม หน่วยการทำงานของการศึกษานี้ คือ ปริมาณหนึ่งตันของความต้องการใช้ผลิตภัณฑ์ปิโตรเลียมในประเทศไทยในปี 2560 แนวทางการจัดการน้ำมันหล่อลื่นที่ใช้แล้วทั้ง 5 วิธี ที่ได้พัฒนาขึ้น ได้แก่ การจัดการแบบกรณีฐานหรือแนวทางการจัดการที่ใช้อยู่ในปัจจุบัน (วิธีที่ 1) การจัดการแบบไม่มีการผลิตใหม่ (วิธีที่ 2) การจัดการด้วยวิธีการกลั่น (วิธีที่ 3) การจัดการด้วยวิธีการกลั่นซ้ำใหม่แบบ KTI (วิธีที่ 4) และ การจัดการด้วยวิธีการกลั่นซ้ำใหม่แบบ Revivoil (วิธีที่ 5) ผลวิเคราะห์การไหลของวัสดุแสดงการแบ่งสัดส่วนของวิธีการจัดการของของเสีย ซึ่งพบว่าผลิตภัณฑ์ทุติยภูมิส่วนมากประกอบไปด้วย น้ำมันดีเซลร้อยละ 68 รองลงมาคือ ยางมะตอยร้อยละ 20 ผลการประเมินวัฏจักรชีวิตแสดงให้เห็นถึงการประเมินทางสิ่งแวดล้อมของแต่ละวิธีการจัดการ กล่าวคือ ค่าศักยภาพในการทำให้เกิดภาวะโลกร้อนส่วนมากเกิดจากการใช้ผลิตภัณฑ์ ส่วนวิธีการกลั่นซ้ำใหม่แบบ KTI ก่อให้เกิดค่าผลกระทบน้อยที่สุดเท่ากับ -1,356 กิโลกรัมคาร์บอนไดออกไซด์เทียบเท่า รองลงมาได้แก่ วิธีการกลั่นซ้ำใหม่แบบ Revivoil ที่ก่อให้เกิดค่าผลกระทบทางสิ่งแวดล้อม เท่ากับ -733 กิโลกรัมคาร์บอนไดออกไซด์เทียบเท่า ในขณะที่วิธีการจัดการแบบกรณีฐานก่อให้เกิดค่าผลกระทบทางสิ่งแวดล้อม ประมาณ 24 เท่าของวิธีการกลั่นซ้ำใหม่แบบ KTI ซึ่งเป็นวิธีที่ได้ค่าผลกระทบน้อยที่สุด ดังนั้นแล้ววิธีการกลั่นซ้ำใหม่แบบ KTI จึงเป็นเทคโนโลยีที่เหมาะสมที่จะมาแทนที่แนวทางการจัดการในปัจจุบัน เพื่อการจัดการน้ำมันหล่อลื่นที่ใช้แล้วอย่างยั่งยืน

GRAPHICAL ABSTRACT

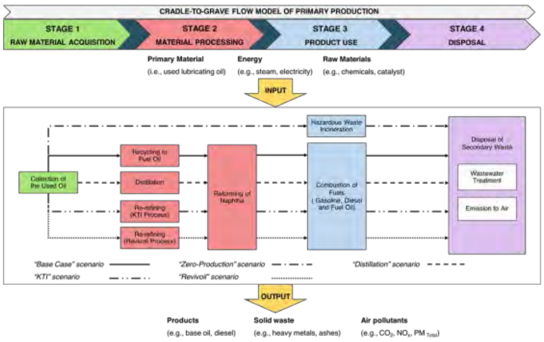
Scope of Material flow analysis of used lubricating oil management (MFA)

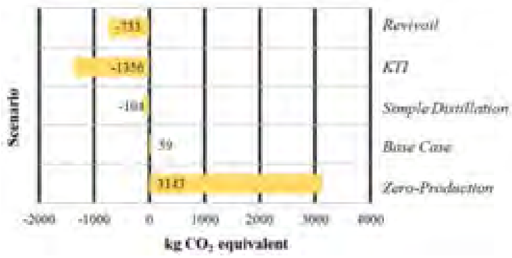




The Material flow analysis (MFA) in STAN software

Scope of Life cycle assessment (LCA) of used lubricating oil management





Scope of Life cycle assessment (LCA) of used lubricating oil management

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CHAPTER I
INTRODUCTION

1.1 Introduction

Thailand has experienced dramatic growth in the number of automotive industries including auto services. This has led to higher consumption of maintenance and operational products, such as lubricating oil. The used lubricating oils are one of the primary concerns about waste management.

The main problem of the used lubricating oils is that they are classified as hazardous waste because they are composed not only of hydrocarbons but also heavy metals, e.g., Cr, Ni, Pb, Al, Si and Zn. Therefore, their disposal requires proper handling and treatment to reduce the severe impact on the environment and human health. In addition, the surge in the number of vehicles causes increasing difficulty with waste management and disposal. The utilization of used lubricating oils has people's attention due to its economic benefits. Many waste utilizations have been developed to convert the used waste oil into a new valuable product. For example, re-refining the used waste oil can increase the price of the base oil as it can reduce the spending on waste management.

Several environmental management tools have been intensively used to assess and improve the waste management system regarding the future development of waste management in the country level. Material flow analysis (MFA) is one of the tools that provide a system-oriented view of linked waste flows to develop and then design management schemes. Life cycle assessment (LCA) is one of the tools that evaluate impacts on the environment that occur by activities and processes from the raw materials to finished products. Although MFA and LCA are well-known tools for environmental management, these tools have been often used independently rather than together. In this study, MFA and LCA are combined as a tool for assessing the most appropriate alternatives for end-of-life scenarios.

The treatment scenarios are divided into five options, namely (i) the base case or current practice, (ii) the zero-production, (iii) the distillation, (iv) the re-refining by KTI process and (v) the re-refining by Revivoil process. The re-refining is widely used in many countries nowadays. Since the system-oriented waste boundary and inventory of each stage during the waste processes are laborious to conduct, the MFA is applied in this study to determine systematically the waste flow using STAN software. The LCA is also conducted to evaluate the environmental impact of each alternative.

The purpose of this research is to demonstrate the waste flow data of the used lubricating oil and their properties, especially, e.g., heavy metals. The second is to evaluate the environmental impacts of used lubricating oil management schemes for each scenario. Finally, the third is to select the appropriate scenario as the future sustainable solution end-of-life for used lubricating oil management.

1.2 Objectives

- To overview the data of used lubricating oil that are collected.
- To set the system boundary and inventory of used lubricating oil through an end-of-life approach.
- To study mass flow analysis (MFA) and life cycle assessment (LCA) for simulating results from each scenario in Thailand.
- To determine the environmental impacts that are occurred in each scenario.
- To find the appropriate scenario of used lubricating oil management that are suitable due to environmental sustainability.

CHAPTER II
LITERATURE REVIEW

2.1 Lubricating Oil

Lubricating oil, so-called lubricant or lube oil, is a class of oils used to lessen friction and to reduce the heat generated between mechanical components that are in contact at its surface each other. Most of the lubricating oils are motor oils, which are specially used in motorized vehicles, whereas lubricating oils used in an automotive application are also used in mechanical equipment, such as turbines, pumps and wears, of which, they are called as engine oil (Audibert, 2006).

Lubricating oils are divided into two main groups: mineral oils and synthetic oils. Mineral oils are lubricating oil refined from natural crude oil, while synthetic oils are lubricating oils. Mineral lubricating oils are widely used because they are a low-cost product by refining from crude oil.

Nevertheless, lubricating oils blended from both of the two together are currently the most used in vehicles and equipment because mineral oils can be manufactured with varying properties, e.g., viscosity, flash point, pour point, fire point, and API gravity. Therefore, making of a proper property is useful in a wide range of applications.

2.1.1 Lubricating Oil Classification

Lubricating oil is classified by the American Petroleum Institute (API) and Society of Automotive Engineers (SAE) for settlement quality and performance standards in order to control lubricant quality from lubricant manufacturers that attach label shown API and SAE standards on the products.

API classification is mainly divided into two types: gasoline engine oil and diesel engine oil. Gasoline engine oil is used in gasoline vehicles, e.g., car, van, light truck and motorcycle. Oils designed for gasoline-engine service fall under API's "S" categories. "S" stands for spark ignition related to the performance of gasoline engine. Oils designed for diesel-engine service fall under API's "C" categories. "C" stands for compression ignition related to the performance of diesel-engine.

Diesel oil is used in large-size vehicles, e.g., heavy truck, ship, bus, military vehicle and heavy equipment. In addition, the lubricating oil designed for gasoline-engine might also be used in diesel engines. The designation is “S” category first followed by the “C” category for multiple performances of the lubricating oil. In the same way, diesel-engine oil can also be used in gasoline engines. For these oils, the designation is “C” category first followed by the “S” category. Primary letter category identifies priority over the use of oil in a suitable type of engine. For instance, CK-4/SN give more effective performances in diesel-engine compared to SN/CK-4.

Table 2.1 API category of lubricating oils in gasoline-engine

Category	Status	Service
SN	Current	Current highest available standard
SM	Current	Car engines is available for 2010 model and older model.
SL	Current	Car engines is available for 2004 model and older model.
SJ	Current	Car engines is available for 2001 model and older model.
SA to SH	Obsolete	Not suitable for use in any gasoline-powered engine.

Table 2.2 API category of lubricating oils in diesel-engine

Category	Status	Service
CK-4	Current	Current highest available standard
CJ-4	Current	Car engines is available for 2010 model and older model.
CI-4	Current	Car engines is available for 2004 model and older model.
CH-4	Current	Car engines is available for 1998 model and older model.
CA to CG-4	Obsolete	Not suitable for use in any diesel-powered engine.

Table 2.1 and Table 2.2 present API category of lubricating oil for gasoline-engine and diesel-engine, respectively. This information suggests the most suitable kind of lubricating oils for one's car. Moreover, each grade of the lubricating oil has a different characteristic which affects the management of its waste. That is, recent lubricating oil is produced to apply with the more complex engine because the current model year requires more specific properties of the lubricating oils.

Consequently, managing conditions in pre-treatment are different depending on types of a lubricating oil. SAE classification is defined in terms of viscosity grades of engine oil for passenger cars. Viscosity grade is the measure of an oil's thickness and ability to flow at certain temperatures in order to assure that lube oil can be operated under extremely hot or cold conditions. Lubricating oil is thin enough to flow at low temperatures and thick enough to perform satisfactorily at high temperatures. According to viscosity characteristics, SAE created the code system to grade motor oils. Because of the oil's viscosity changes with temperature, motor oils were developed to provide protection across the range of temperatures

SAE code: SAE xxW

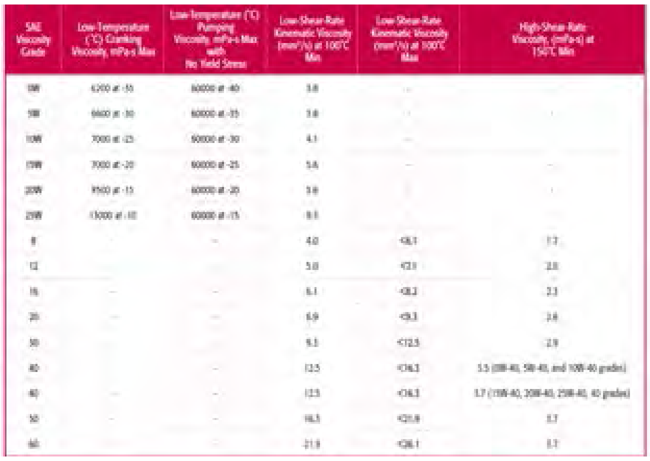
Where, xx = viscosity grade at cold temperature

W = Winter

SAE code: SAE yy

Where, yy = viscosity grade at 100 °C

Most motor oils currently fulfill at cold temperature and high temperatures, which is called multigrade oils. Their viscosity grade consists of two numbers, e.g., 5W-30 that 5W refers to the viscosity grade at cold temperature and 30 refers to the high-temperature viscosity.



SAE Viscosity Grade	Low-Temperature (°C) Cranking Viscosity, mPa-s Max	Low-Temperature (°C) Pumping Viscosity, mPa-s Max with No Yield Stress	Low-Shear-Rate Kinematic Viscosity (mm²/s) at 100°C Min	Low-Shear-Rate Kinematic Viscosity (mm²/s) at 100°C Max	High-Shear-Rate Viscosity, (mPa-s) at 150°C Min
0W	6200 at -35	60000 at -40	3.8	–	–
5W	6600 at -30	60000 at -35	3.8	–	–
10W	7000 at -25	60000 at -30	4.1	–	–
15W	7000 at -20	60000 at -25	5.6	–	–
20W	9500 at -15	60000 at -20	5.6	–	–
25W	13000 at -10	60000 at -15	9.3	–	–
8	–	–	4.0	<6.1	1.7
12	–	–	5.0	<7.1	2.0
16	–	–	6.1	<8.2	2.3
20	–	–	6.9	<9.3	2.6
30	–	–	9.3	<12.5	2.9
40	–	–	12.5	<16.3	3.5 (0W-40, 5W-40, and 10W-40 grades)
40	–	–	12.5	<16.3	3.7 (15W-40, 20W-40, 25W-40, 40 grades)
50	–	–	16.3	<21.9	3.7
60	–	–	21.9	<26.1	3.7

Figure 2.1 Lubricating Oil Viscosity Classification (SAE, 2015).

2.2 Used Lubricating Oil

After due use, used lubricating oils are still a valuable resource. They are classified as hazardous wastes because used lube oils contain various contaminants, e.g., sludge, heavy metals, wastewater, sulfur, etc. Among them, heavy metals are especially the most harmful contaminants contained which bring severe problems to the environmental impacts and human health.

Table 2.3 The composition of used lubricating oil from survey study and journal review (Zubaidi *et al.*, 2018)

No.	Waste Type	Amount (wt%)	
		Survey study	**Journal review[a]**
1	Lubricating oil	86.01	86.72
2	Fuel	6.69	7.50
3	Contaminated water	0.27	1.30
4	Sulfur	0.74	0.90
5	Heavy metals	< 0.01	< 0.10
6	Suspended substances	6.29	3.48
Total used lubricating oil		100.00	

Table 2.4 Physical properties of used lubricating oils (Zubaidi *et al.*, 2018)

Physical property	ASTM method	Amount	Unit
Specific gravity at 20 °C	ASTM D 1298	0.886	
Flash point	ASTM D 93	142	°C
Water and Sediment	ASTM D 96	1.3	% volume
Viscosity at 37.8 °C	ASTM D 445	208.84	cSt
Carbon residue	ASTM D 189	1.169	% weight
Ash content	ASTM D 582	0.449	% weight
Asphalting content	ASTM D 3279	1.876	% weight
Sulfur content	ASTM D 2622	0.899	% weight
Salt content	ASTM D 3230	43.7	ppm
Heating value	ASTM D 4809	44,766	kJ/kg

Table 2.5 Metal content of used lubricating oil (Zubaidi *et al.*, 2018)

Metal	ASTM method	Content (ppm)
Aluminum (Al)	ASTM D 5185-9	29
Silicon (Si)	ASTM D 5185-9	557
Iron (Fe)	ASTM D 5185-9	32
Lead (Pb)	ASTM D 5185-9	11
Chromium (Cr)	ASTM D 5185-9	< 1
Copper (Cu)	ASTM D 5185-9	3

2.3 Oil Standard Specification

Used lubricating oils are a valuable resource for providing many benefits, including recycling to new products, e.g., base oil, petroleum gas, gasoline, diesel, asphalt and fuel oil. However, the new products contain several obsolete contaminants that have effects on the environment. Oil standard specifications were regulated by the Department of Energy Business, Thailand (DOEB) in order to specify the appearance and quality of the new products that are suitable and in accordance with international standards.

Table 2.6 Specification of liquefied petroleum gas (DOEB, 2018)

No.	Item	Unit	Limit	Liquefied petroleum gas (LPG)
1	Water dew point at pressure	°C MPa	Max	4.4 20
2	Hydrocarbon dew point at pressure	°C MPa	Max	10 4.5
3	Methane number		Min	65
4	Hydrogen sulfide	mg/m^3	Max	23
5	Hydrogen	Vol%	Max	0.1
6	Carbon dioxide	Vol%	Max	15
7	Oxygen	Vol%	Max	1
8	Sulfur	mg/m^3	Max	50

Table 2.7 Specification of gasoline (DOEB, 2012)

No.	Item	Unit	Limit	Gasoline
1	Octane number (RON) Octane number (MON)		Min Min	94.6 83.6
2	Lead	g/L	Max	0.005
3	Sulfur	% weight	Max	0.005
4	Phosphorus	g/L	Max	0.0013
5	Residue	Vol%	Max	2.0
6	Benzene	Vol%	Max	1.0
7	Aromatics	Vol%	Max	35.0
8	Olefins	Vol%	Max	18.0
9	Water	% weight	Max	0.7

Table 2.8 Specification of diesel (DOEB, 2007)

No.	Item	Unit	Limit	Diesel		
				HSD		LSD
				Normal	B5	
1	Specific gravity at 15.6 °C		Min	0.81	0.81	-
			Max	0.87	0.87	0.92
2	Cetane number		Min	50	50	45
3	Viscosity at 40 °C	cSt	Min	1.8	1.8	-
		cSt	Max	4.1	4.1	8.0
4	Pour point	°C	Max	10	10	16
5	Flash point	°C	Min	52	52	52
6	Sulfur	% weight	Max	0.005	0.005	1.5
7	Water and Sediment	Vol%	Max	0.05	0.05	0.3
8	Ash	% weight	Max	0.01	0.01	0.02
9	Carbon residue	% weight	Max	0.05	0.05	-
10	PAH	% weight	Max	11	11	-

Table 2.9 Specification of base oils (DOEB, 2016)

No.	Item	Unit	Limit	Viscosity grade			
				0W	10W	20W	25W
1	Viscosity at temperature of	cP °C	Max	6,200 -35	7,000 -25	9,500 -15	13,000 -10
2	Viscosity at 100 °C	cSt	Min	3.8	4.1	5.6	9.3
3	Flash point	°C	Min	182	182	199	199
4	Water	Vol%	Max	0.05	0.05	0.05	0.05
5	Sediment	Vol%	Max	0.07	0.07	0.07	0.07

Table 2.10 Specification of light fuel oil (DOEB, 2004)

No.	Item	Unit	Limit	Fuel oil[a]			
				Type I	Type II	Type III	Type IV[b]
1	Viscosity at 50 °C	cSt	Min	7	81	181	231
		cSt	Max	80	180	230	280
2	Specific gravity at 15.6 °C		Min	0.985	0.990	0.995	
3	Pour point	°C	Max	24	24	30	30
4	Flash point	°C	Min	60	60	60	60
5	Gross heat of combustion	kcal/g	Min	10	9.9	9.9	9.9
6	Water and Sediment	% volume	Max	1.0	1.0	1.0	1.0
7	Ash	% weight	Max	0.1	0.1	0.1	0.1

Note: Explanatory legend is expressed below Table 2.9.

a) Type of fuel oil has been accepted by the International Organization for Standardization (ISO).

b) Fuel oil type IV is called Bunker fuel.

Table 2.11 Specification of heavy fuel oil (DOEB, 2004)

No.	Item	Unit	Limit	Heavy fuel oil[a]
1	Viscosity at 100 °C	cSt	Min	3
		cSt	Max	30
2	Specific gravity at 15.6 °C		Min	0.995
3	Pour point	°C	Max	57
4	Flash point	°C	Min	60
5	Gross heat of combustion	kcal/g	Min	9.9
6	Water and Sediment	Vol%	Max	1.0
7	Ash	% weight	Max	0.1

Note: Explanatory legend is expressed below Table 2.10.

a) Heavy fuel oil is defined as fuel oil type V.

2.4 Waste Management

Sustainable waste management protects human health, the environment and prevents the export of waste-related problems in the future. In order to enable a dialogue between consumers, policy-makers, authorities and researchers about waste management. The European Commission's Waste Framework was published to make recommendations on the waste treatment option and the waste hierarchy shown in Figure 2.2 that is applicable across the European Union.

The current waste management practices are rigorously influenced by the waste hierarchy, which recommends a priority order from the most preferred option at the top to the least preferred option at the bottom (Gharfalkar *et al.*, 2015).

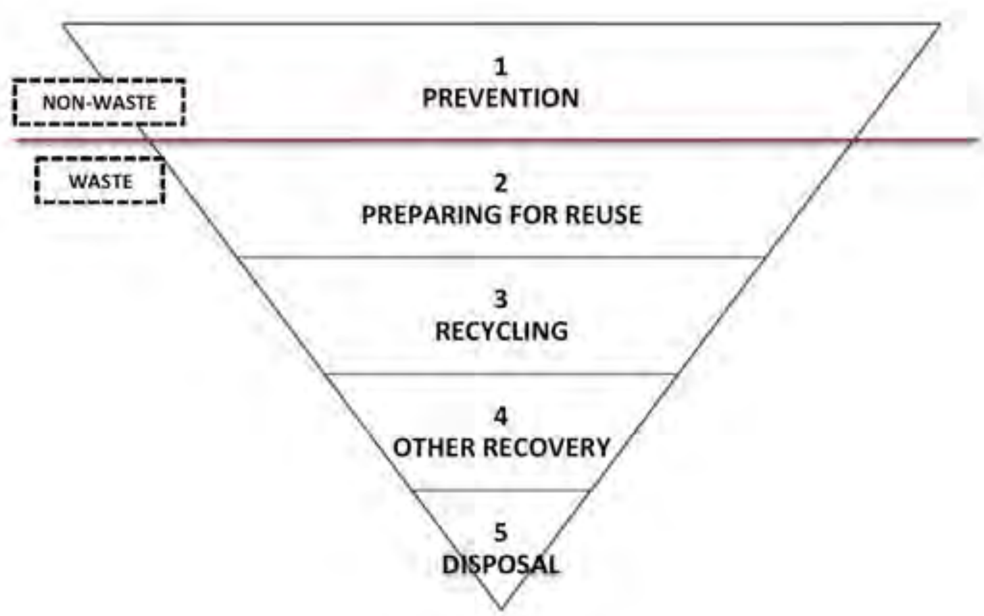


Figure 2.2 Waste hierarchy (Gharfalkar *et al.*, 2015).

Waste hierarchy is divided into five steps ranked by the most preferred option at the top to the least preferred option at the bottom with reference to the Waste Framework Directive hierarchy in 2008 (WFD2008).

1. Prevention

Prevention step is the first step to deal with wastes that materials and products from processes began to turn into wastes, such as reduction in the content of harmful substances in materials and products, reduction in the amount of wastes and guiding the impact of wastes on the environment and human health.

2. Preparing for reuse

Preparing for reuse step focuses on repairing, checking, cleaning or reusing methods so that they can be used again without any other pre-processing. The major difference between preparing for reuse and reuse is that materials must not become wastes in case of preparing for reuse, while the material has become waste in the case of preparing for reuse. Preparing for reuse step leads to operations by which products or components are used again for the same purpose.

3. Recycling

Recycling step is about recovery operation by which waste materials are reprocessed into products, materials or substances for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing of materials that are used as fuels or for backfilling operations. This step leads to operations that serve a useful purpose by replacing other materials. These operations would have been used to fulfil a particular function.

4. Other recovery steps

Other recovery steps such as combustion, pyrolysis, gasification and anaerobic digestion are similar to recycling step, but unlike the recycling, the other recovery steps only deal with intangible substance, e.g., power, heat, electricity and fuels to produce energy.

5. Disposal

Disposal step is any unrecoverable operation even there has as a secondary consequence the reclamation of substances or energy. This step should be rectified to make waste suitable before disposing of waste by, e.g., landfill, incineration.

2.4.1 Fuel Blending

Fuel blending, which categorizes as recycling step, is the combination of the different kind of fuels including additives to produce the finished products. Focusing on the used lubricating oil, it is suitable to blend with flesh diesel for an increase of the amount of diesel products because the demand of the diesel is still growing at faster rate nowadays (Audibert, 2006).

2.4.2 Reprocessing

Reprocessing categorizes as the recycling step which is able to recover into the new products, e.g., recovery fuel oil, diesel oil, vacuum gas oil, and also asphalt flux as a by-product. Reprocessing mostly needs distillation unit in process to upgrade product quality.

Table 2.12 Physical and chemical properties of diesel oil compared with diesel oil from used lubricating oil (Gabiña *et al.*, 2016)

Property	Unit	Diesel oil from crude oil	Diesel oil from used oil
Density at 15 °C	kg/m^3	850.3	836.6
Viscosity at 40 °C	mm^2/s	20.8	2.9
Viscosity at 100 °C	mm^2/s	4.2	2.9
Flash point	°C	310.0	68.0
Cetane number		56.8	53.0
Low heating value	kJ/kg K	46649.0	44935.0
Sulfur content	ppm	58.0	22.0
Carbon content	%	85.9	86.2
Hydrogen content	%	14.1	13.6
Nitrogen content	%	< 0.1	< 0.1

Reprocessing to produce recovery fuel oil (RFO), diesel oil (DO) and vacuum gas oil (VGO) requires energy and material input, such as natural gas for heating and electricity for pressurization and pumping. The processes employed to produce the new product and the asphalt flux involve distillation to remove light ends, water and heavy oil distillate from contaminants also called bottoms. The heavy metals and other contaminants of the used lubricating oil in the asphalt flux via distillation could result in some risk. However, Toxicity Characteristic Leaching Procedure (TCLP) shows that the heavy metals are bound within the tar matrix and insignificant leaching occurs. These results are contained in the California Department of Toxic Substances Control Lab Report. According to the official results, Asphalt flux can be used as an extender for virgin asphalt materials, asphalt concrete additive, or for other traditional asphalt bitumen uses (Boughton *et al.*, 2004).

Table 2.13 Input and output of the distillation process based on DeMenno/Kerdoon Inc. in optimum operation (Boughton *et al.*, 2004)

Input	**Unit**	**Reprocessing**
Used oil	kg	1000
Caustic soda	kg	3.1
Natural gas	kg	1851.9
Electricity	kWh	89.5
Output	**Unit**	**Reprocessing**
Asphalt	kg	520
Diesel oil	kg	440
Light ends	kg	40

2.4.3 Re-refining

Re-refining processes as recycling step which is able to recover into a new base oil that is the more valuable product comparing with reprocessing and fuel blending. In addition, re-refined base oils have good properties and are flexible to use for various purposes. Re-refining process outstandingly enhances economic efficiency and reduce contamination in oils. Re-refining results in recovery of a high-purity lubricating base oil which displaces original base oil. The heavy metals and other contaminants in used lubricating oil are concentrated in the asphalt by-product of the re-refining process (Boughton *et al.*, 2004). The various processes of re-refining of used lubricating oil to base oil were explained the details that provide a range of performance and burden data across the process examples.

Pires and coworkers (2013) concluded that re-refining and energy recovery was considered to be good recovery options depending on impact reviewed. However, re-refining is the preferable option with reference to the Waste Framework Directive hierarchy. This study uses Life Cycle Assessment (LCA) as an evaluation tool.

1. Cyclon process

The Cyclon process has been developed by Kinetic Technology International (KTI). Greek Cyclon Hellas Company currently uses this technology with an annual capacity of 40,000 tons. The process flow diagram of the Cyclon process is illustrated in Figure 2.3. Firstly, used lubricating oils are dewatered and then the light hydrocarbons are separated and removed by the vacuum distillation. Next, the heavier fraction is sent to the high vacuum distillation, where most of oil components are evaporated from the heavy residue. The oils in the residues are extracted with propane in the de-asphalting unit that gives the asphalt flux as a by-product. Finally, they are treated by hydrogen with the catalyst at a temperature of 300 °C and fractionated based on the desired base oil (Kupareva *et al.*, 2013).

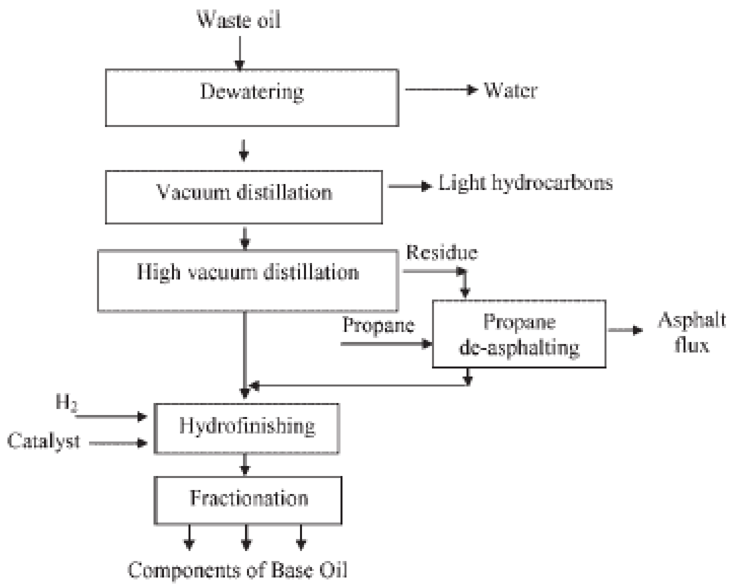


Figure 2.3 Flow diagram of Cyclon process (Kupareva *et al.*, 2013).

2. Hylube process

The Hylube process has been developed by Universal Oil Products (UOP) for the catalytic processing of used lubricating oils into re-refined lube base stocks. This process unit has been successfully commercialized by Puralube, located in Germany, currently using technology licensed (N. Kalnes *et al.*, 2006). The Hylube process is specially received used oil without any pre-treatment. The common process feedstock is composed of a blending of used lubricating oils with high of the heavy metals such as Fe, Zn and Ca. The block flow diagram of the process is shown in Figure 2.4. Firstly, the used lubricating oil is sent into flash-separation to separate heavy components called residue from the light components. Secondly, the light feed is transformed through the guard reactor where metal metal-containing compounds and impurities are accumulated in the large pore size catalyst.

Next, the treated feed is sent into the conversion reactor at a temperature in the range 300-350 °C with the pressure of 60-80 bar to enhance the quality of base oil. Then, products are fed to the high-temperature separator that separate light ends and heavy ends. Light ends are blended with demineralized water and sodium hydroxide and then flowed into the cold-temperature separator for removing the wastewater and also separating rich vapor of hydrogen to return into the mixer. Finally, light ends and heavy ends are collected and sent to the fractionation section where the products are separated into various cuts to meet the desired lube oils (Kupareva *et al.*, 2013).

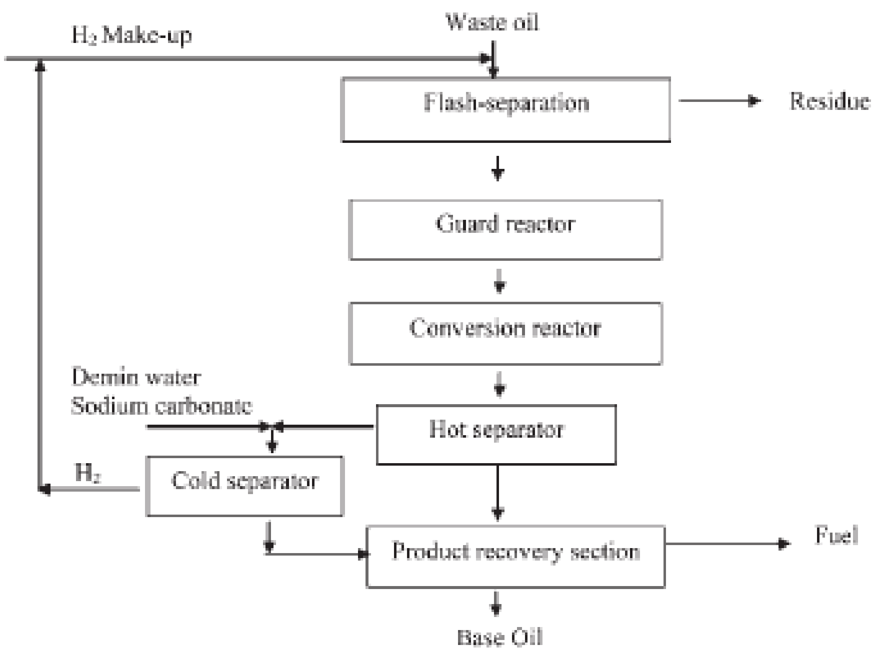


Figure 2.4 Flow diagram of Hylube process (Kupareva *et al.*, 2013).

3. MRD (Mineralöl-Raffinerie Dollbergen)

The MRD process has been developed since 1955 by Mineralöl-Raffinerie. This refinery has the capacity of 120,000 tons/year of used lubricating oil to produce the recycled base oil about 70,000 tons/year.

The MRD process uses N-methyl-2-pyrrolidone (NMP) solvent, which is commonly used in the petroleum refining industry. Due to its relative non-reactivity and high selectivity, NMP is used as an aromatic extraction solvent in the lubricating oil re-refining. The advantages of NMP over other solvents are high solvent power without toxicity effect. Figure 2.5 provides the flow chart of the MRD process. Firstly, the used lubricating oil is dewatered and then fed to the vacuum distillation for the separation of light hydrocarbons from residue. Secondly, the residue dissolved oxygen in the distillate is removed in an absorber using steam before entering extraction column. Then, the distillate is sent to the bottom of the extraction column where contaminants are separated out by the counter-flowing heavier NMP solvent fed in at the top of the column. In addition, the solvent containing raffinate phase leaves at the top of the column and is routed to the downstream raffinate recovery section in which the solvent is removed. the remaining fraction is a base oil as the desired product.

The extract phase is removed from the bottom of the extraction column and then separated in a separation drum to segregate the separated secondary raffinate. The extract phase from the secondary separation drum is sent to the extract recovery section where the solvent is removed. The resulting extract is used as a component for heavy oil, and the dry NMP solvent separated in the distillation columns of the raffinate and extract recovery sections is returned to the solvent tank. (Kupareva *et al.*, 2013).

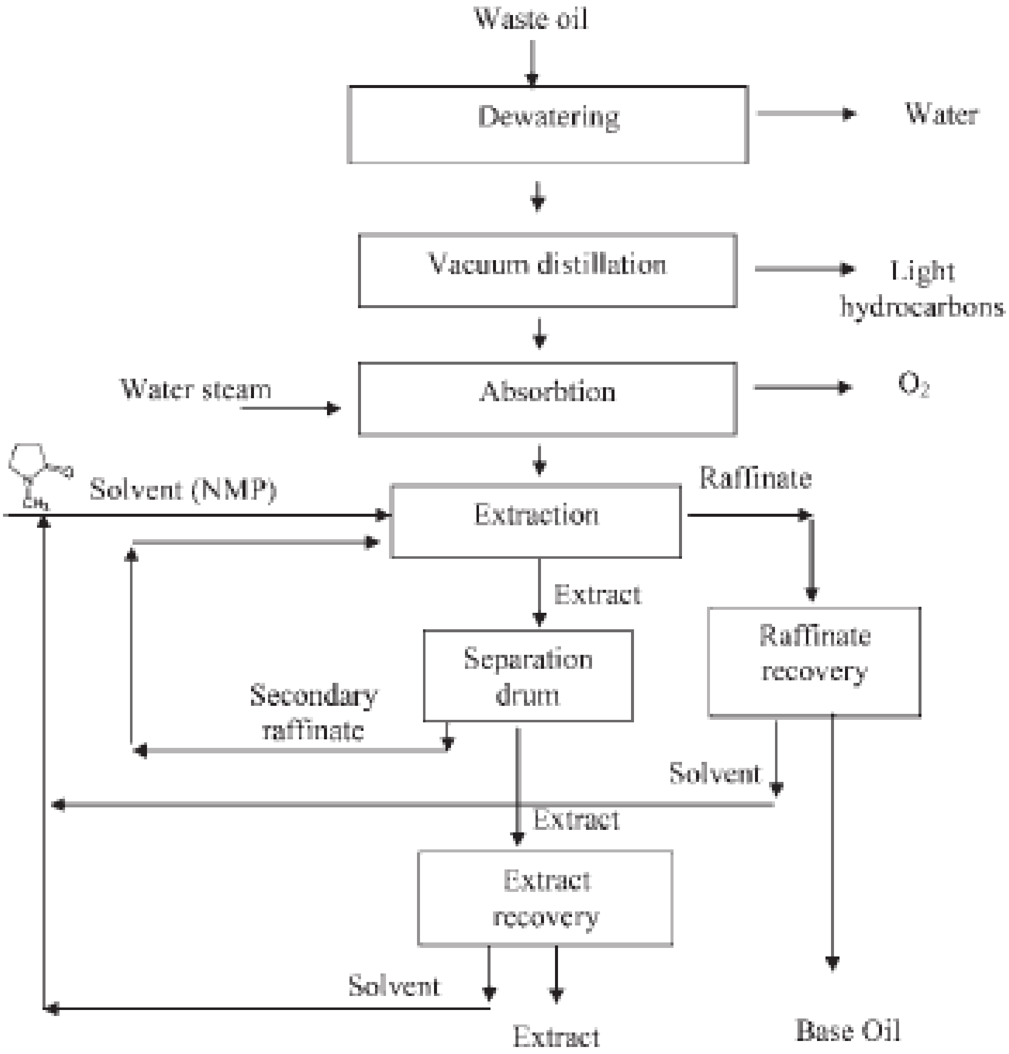


Figure 2.5 Flow diagram of MRD solvent extraction process (Kupareva *et al.*, 2013).

Table 2.14 Input and output of re-refining technique (Boughton *et al.*, 2004)

Input	**Unit**	**Cyclon**	**Hylube**	**MRD**
Used oil	kg	1000	1000	1000
Caustic soda	kg	0.71	4.67	0
Potassium hydroxide	kg	0	0	0.06
Hydrogen	kg	2.02	5.16	0
Soda ash	kg	0	8.41	0
Propane	kg	2.25	0	0
NMP solvent	kg	0	0	0.06
Electricity	MJ	283	875	122
Process heat	MJ	2420[a]	1360[a]	622[a]
Process steam	MJ	617	632	1630
Process water	MJ	0	374	0
Output	**Unit**	**Cyclon**	**Hylube**	**MRD**
Base oil	kg	725.2	770.8	544.5
Naphtha	kg	0[b]	37.6	0
Light ends	kg	14.2[b]	0	25.0
Extracts	kg	0	0	78.0
Flux oil	kg	82.2[c]	0	29.3[c]
Light fuel oil	kg	99.2	75.2	0
Heavy oil	kg	0	56.4[d]	137.3
Residue	kg	0	0	123.6
Used process water	kg	79	433.8	59.7
Energy delivery	MJ	707	0	7500

Note: Explanatory legend is expressed from Table 2.13

a) Process heat and steam are assumed to be produced by natural gas.

b) 14.2 kg of light ends can particularly be converted into naphtha.

c) Flux oil is used as an additive in the bitumen.

d) Heavy oil is applied as a reduction material within a blast furnace.

4. Revivoil

The Revivoil process has been developed since June 2003 by Viscolube and the French Institute of Petroleum (IFP). The refinery that using this technology was located in Italy. It has operated at a maximum capacity of 80,000 tons/year of used oil to produce the recycled base oil. This process combines thermal deasphalting (TDA) licensed by Viscolube company with catalytic hydrogenation licensed by the ITP. Thermal deasphalting is vacuum distillation upstream that consists of distilling in a high vacuum dehydrated oil at the pressure of 15 absolute torrs to separate sulfur species out of oil product. After thermal deasphalting, the residue from distillation is fed into the propane deasphalting process for propane recovery into the hydrogenation process. While others are separated into light hydrocarbons, medium hydrocarbons, heavy hydrocarbons. Finally, they are fed into the catalytic hydrogeneration unit to enhanced base oil content in its product (Audibert, 2006).

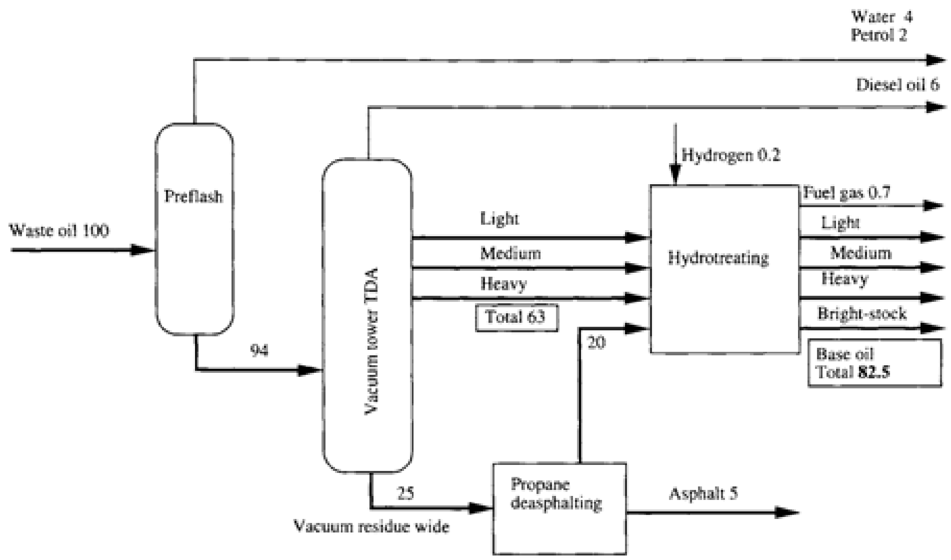


Figure 2.6 Flow diagram of Revivoil process (Audibert, 2006).

5. KTI (Kinetics technology International)

The KTI process has been developed since the 1980s. The first refinery that used this technology was built in Greece in 1982, followed by the other companies in Europe and the US. The KTI has firstly used falling film technology in this process. It has operated at a maximum capacity of 68,000 tons/year of used oil to produce the recycled base oil. This process is required atmospheric distillation to remove the various type of contaminants, e.g., solvents, water, phenol and glycol. Then, the feedstock is sent to vacuum distillation to remove diesel at the top. Next, the bottom is heated and sent to Thin- film evaporator (TFE) unit to remove light oil and create a higher vacuum in the evaporator to keep the maximum quantity of heavier fraction. After that, the heavier fraction is sent to the hydrofinishing reactor to decrease the sulfur, chlorine, nitrogen and heavy metals to the desired level. Finally, the heavier fraction is sent to the fractionation operating at 200 °C with the pressure of 22 torrs for the separation unit into various products, e.g., fuel gas, light hydrocarbons, diesel, and base oil (Audibert, 2006).

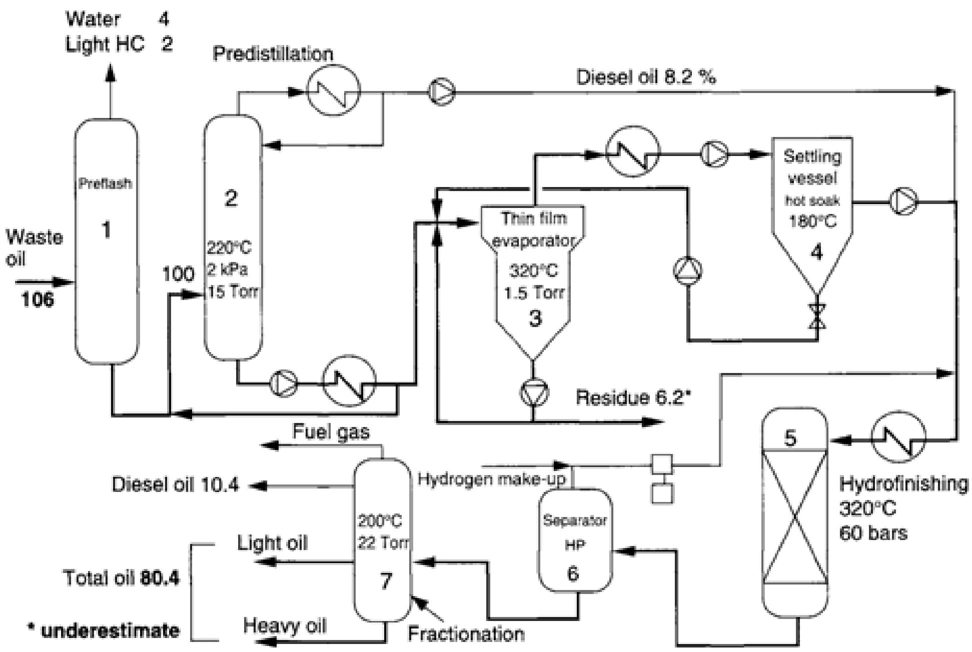


Figure 2.7 Flow diagram of KTI process (Audibert, 2006).

Table 2.15 Input and output of re-refining technique (Audibert, 2006)

Input	**Unit**	**Revivoil**	**KTI**
Used Oil	kg	1000	1000
Additives[a]	kg	10	0.25
Water cooling	kg	226	2000
Power	kWh	55	94
Hydrogen	kg	2.5	2.419
Nitrogen	m^3	0	1.6
Steam	kg	800	26.5[b]
Fuel oil	kg	65	0[c]
Catalyst	kg	0.25[d]	0
Output	**Unit**	**Revivoil**	**KTI**
Base oil	kg	825.00	758.49
Diesel oil	kg	60.00	98.11
Wastewater	kg	40.00	0[c]
Gasoline	kg	20.00	0[c]
Asphalt	kg	50.00	0[c]
Fuel gas	kg	8.75	10.00
Residue oil	kg	0[c]	58.49
Light hydrocarbon	kg	0[c]	18.87

Note: Explanatory legend is expressed below the table.

a) Additives in the used oil are unknown.

b) 7 bar of steam is required for KTI technology.

c) These items are approximately zero.

d) Catalyst in Revivoil process is a zeolite.

2.5 Material Flow Analysis (MFA)

Material flow analysis (MFA), also referred to substance flow analysis, is a quantitative method for determining flows and stocks of materials or substances in a well-defined system. The sum of all inputs into the system must equal to all outputs plus changes in stock. MFA is an important tool to study environmental impacts support planning of sustainable management. (Brunner *et al.*, 2004).

[Mass balance equation]

$$\text{Input} = \text{Output} \pm \text{Stock}$$

The mass balance principle applies on the level of good as well as substance. It must be observed for every process and for the total system. In addition, MFA can evaluate the changes over time within the system also called a dynamic model which provides information about changes in stocks and flows with time-dependent aspects. MFA on the level of substances is essential to assess aspects regarding the quality of material flows, such as the composition of resources or emissions to the environment. It especially evaluates the transport, transformation and storage of valuable goods and hazardous substances. Both are factors to identify risks for human health and the environment (Brunner *et al.*, 2004).

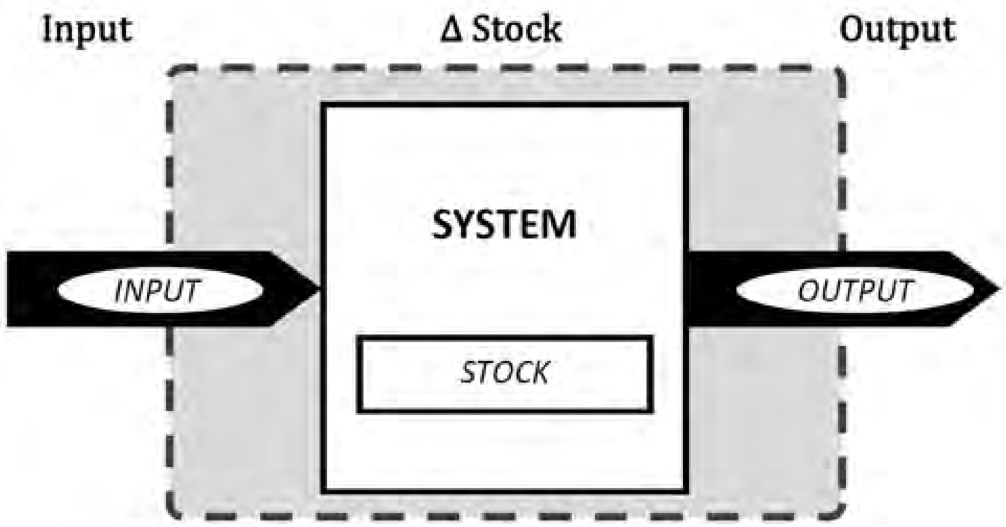


Figure 2.8 Material Flow Analysis (MFA) model (Brunner *et al.*, 2004).

2.5.1 Terminology

The terminology of Material Flow Analysis (MFA) in master's thesis are described in Table 2.15 for guidance in basic principle (Brunner *et al.*, 2004)

Table 2.16 Terminology of Mass Flow Analysis (MFA) (Allesch *et al.*, 2017)

Terms	**Descriptions**
Materials	Any chemical elements or compounds
Goods	Matters with positive or negative economic value that are made up of one or several substances
Processes	Transformation, transport or storage of materials
Flows	Mass flow rate with the ratio of mass per time
Transfer coefficients	The partitioning of materials in a process
System	The actual object of the investigation linking flows and stocks of materials and substances by processes

Kuczenski and coworker (2014) designed a new system for the waste management of used lubricating oil to decrease improper management of used oils which leads to several environmental problems. The waste management system was evaluated by Material flow analysis (MFA) as a tool for presenting a system model and data flows in each process. MFA block diagram defined in Figure 2.9 shows the boxes representing processes and ovals representing stocks that had no accumulation included. Data sources are collected from the automotive and industrial sectors by direct observations. The total quantity of each sector was collectible used oil, including the majority of the used oils which is treated by the formal management, i.e., recycling to fuel oil (RFO), re-refining, distillation and dielectric rejuvenation. However, some of the used oils were particularly treated by the ecologically destructive method called informal management, for instance, combustion, energy recovery and disposal. As a result, informal management should be restricted to alleviate environmental issues.

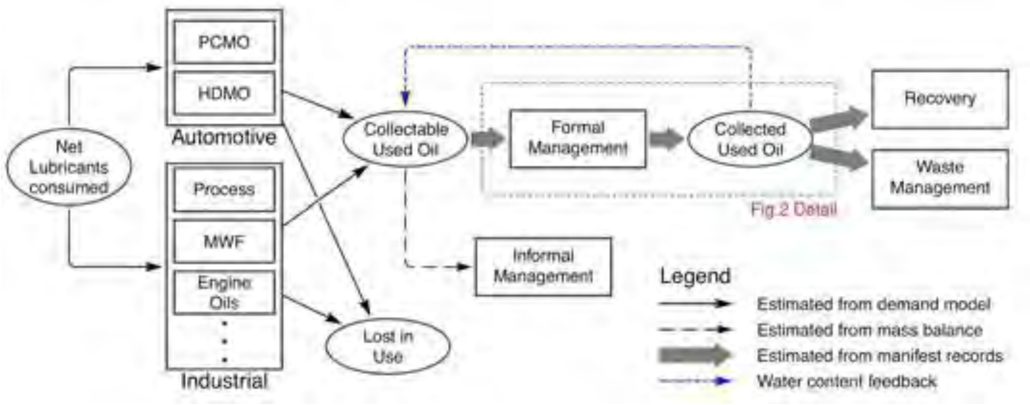


Figure 2.9 MFA diagram of used lubricant management (Kuczenski *et al.*, 2014).

The yearly demand for lubricating oils and recoverability of the formal management in the years 2007-2012 are shown in Figure 2.10. It indicated that the recoverability of used lubricating oil was about 73-80 % from the recoverable used oil by the formal management. Overall, the most commonly used method of formal management was the distillation method. While the least used method was the dielectric rejuvenation method. In terms of the amount of the recovered used oil, it tended to decline gradually from 349 to 291 kilotons. The remain of used oil treated by the informal management was classified as the waste content including wastewater, hazardous waste and unknown compounds.

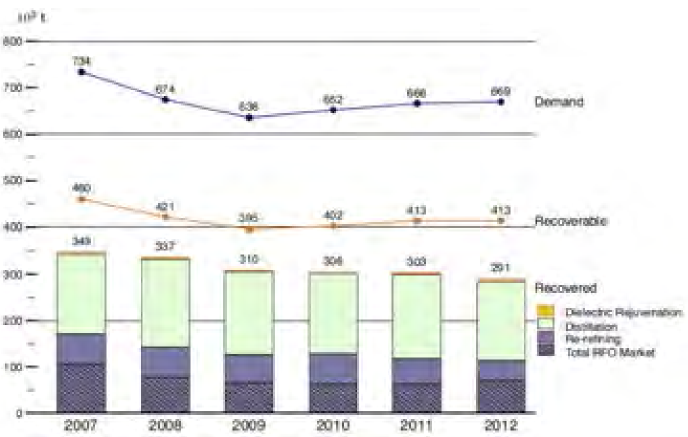


Figure 2.10 Recoverability of used lubricating oil by formal management (Kuczenski *et al.*, 2014).

Jain and coworker (2017) designed the management of a ship recycled yard and evaluated the management system by MFA as the technique to decrease the amount of wastes to landfill. According to Figure 2.11, the boundary system consisted of three major processes, namely pre-cutting, cutting and post-cutting. Firstly, the pre-cutting step was all removal activities that occurred before cutting, such as electrical equipment removal, insulation removal and hazardous material removal. Secondly, the cutting step was the process where ferrous materials were separated from non-ferrous materials. Finally, the post-cutting step was the segregation of Economic Value Stream (EVS) for recycling or reusing EVS, while Non-Economic Value Stream (NEVS) was disposed to landfill.

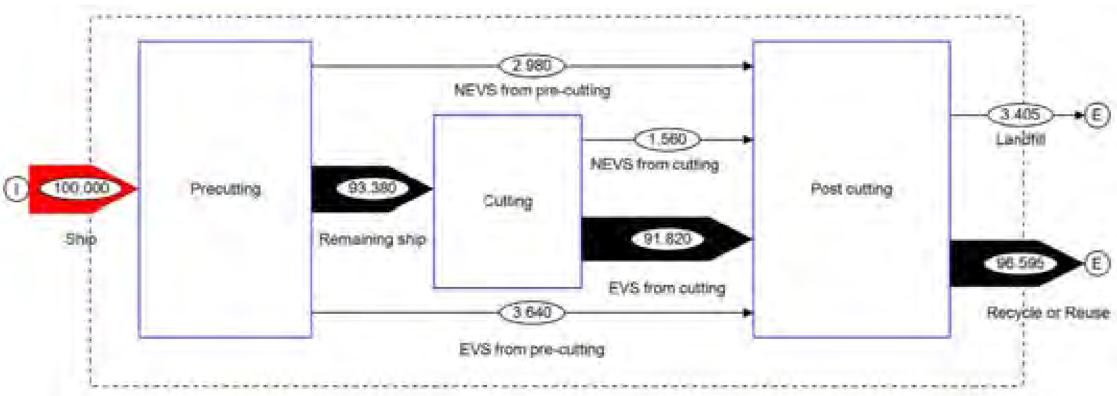


Figure 2.11 MFA diagram of ship recycling (Jain *et al.*, 2017).

According to Figure 2.12, the methodology of the study was defined in 5 steps, namely, indicating the system boundaries, determining the composition of materials by data collection, determining the steps of recycling processes, making the material flow of the system using MFA software and evaluating MFA diagram.

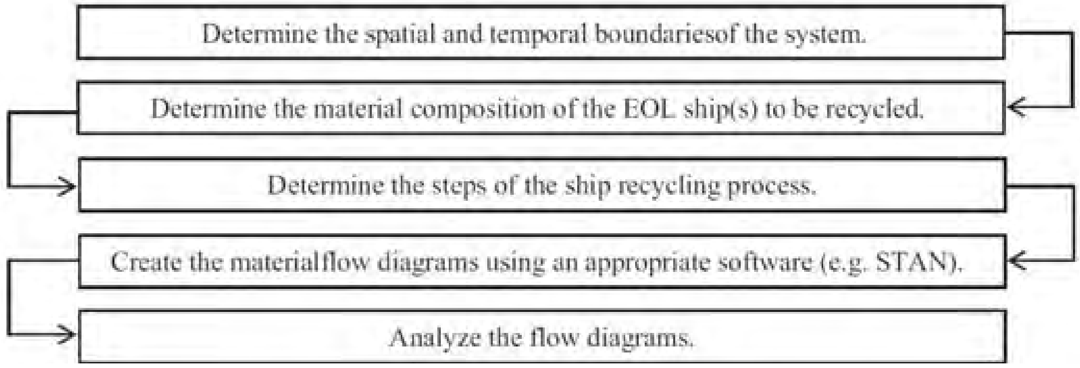


Figure 2.12 Methodology of ship recycling (Jain *et al.*, 2017).

The material streams of the process were considered that all the electronic wastes, the ferrous-scraps and non-ferrous scraps and pieces of machinery were EVS which can be reused and recycled, while all plastics, chemicals and miscellaneous were NEVS which had to treated before disposal at landfills. However, some materials such as mineral and joinery can be classified as both EVS and NEVS. The assumption of material streams led to a significantly different result. The result of MFA was shown in Figure 2.13. It performed the amount of EVS and NEVS based on the percentage of lightweight tons (LDT) from each of sub-processes. Most of the EVS came from the cutting process accounted for 3.4% of the shipping weight which needs to be disposed of, while the others can be recycled and reused.

S.no.	Process	Sub-process	EVS		NEVS	
			Percentage of LDT	Tonnes (rounded up)	Percentage of LDT	Tonnes (rounded up)
1.	Pre-cutting	Removal loose items	0.64	71	0.39	43
2.		Removal liquids	0.50	55	0.50	55
3.		Removal hazardous materials	0.00	0	1.29	142
4.		Removal insulation, flooring, tiling	1.26	139	0.40	44
5.		Removal cables and electrical equipment	1.24	137	0.40	44
6.	Cutting	Primary cutting	92.74	10242	0.64	71
7.		Secondary cutting	87.69	9685	0.92	102
8.	Post-cutting	Pick-up and storage	95.46	10542	4.54	501
9.		Separation	1.14	126	3.40	375
10.		Segregation and transport	96.60	10669	3.40	375

Figure 2.13 The amount of EVS and NEVS from each phase (Jain *et al.*, 2017).

2.6 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is commonly used as an evaluation tool for environmental management. It can be used to determine environmental and human health effects occurred by activity such as material processing, storage, transportation and disposal. Due to the number of available options for waste treatment, LCA guides decision-makers to select the option with more sustainability of environmental impact and also cheaper waste management (Allesch *et al.*, 2014).

Basically, LCA methodology is conducted in four steps.

1. Definition of goal and scope

   To set objectives and system boundaries that give precise results. The goals of all reviewed studies are mainly classified into three categories according to their aims. Table 2.16 describes the definition of goals in the study.

Table 2.17 Type of goals in life cycle assessment (LCA) (Allesch *et al.*, 2014)

Goal	Definition
Scenario-based	a determination method of scenarios to compare each scenario and then find the most appropriate scenario.
Performance-based	a determination method of the project to increase its efficiency
Goal-based	a determination method of the current status of a project with regard to goals and regulations issue.

2. Life-cycle inventory (LCI) analysis

   To collect and calculate material and energy flows using MFA as a tool.

3. Life-cycle impact assessment (LCIA)

   To characterize the environmental effects using the result of MFA data.

4. Life-cycle interpretation

   To analyze and make a summary of data obtained from previous steps of life cycle assessment procedures. The results must base on the scope of the study.

2.4.1 Life Cycle Thinking Boundary

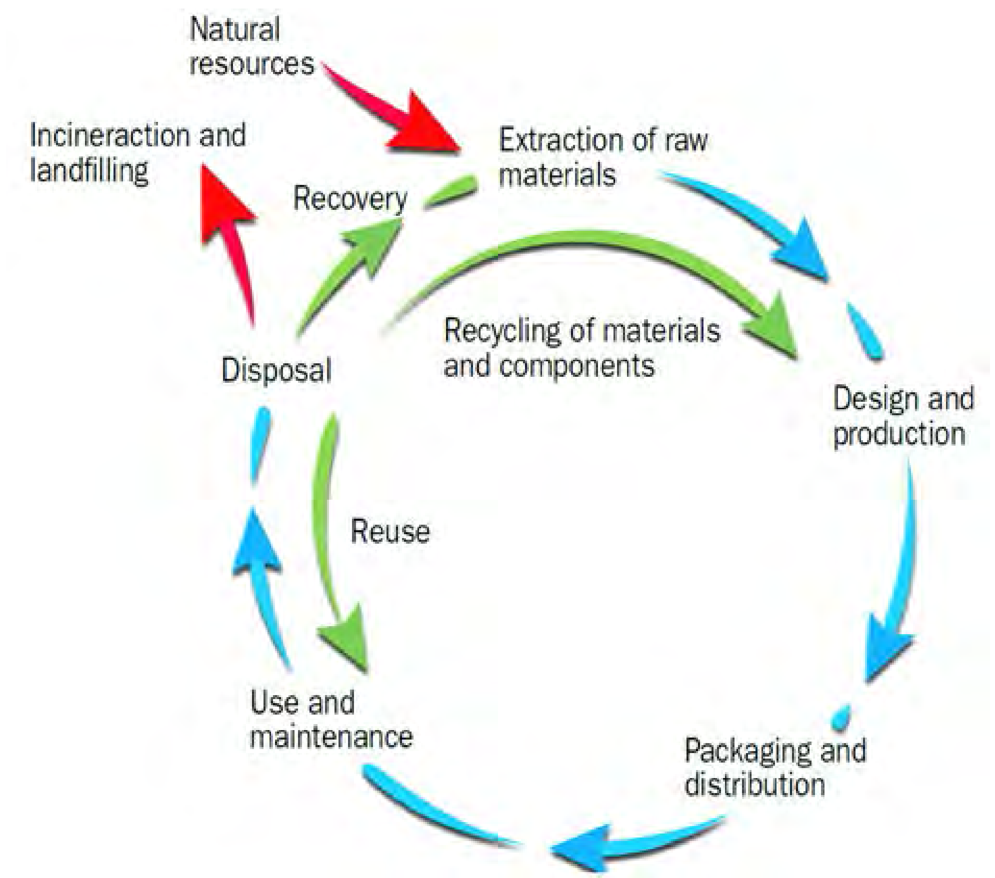


Figure 2.14 LCA iterative process (Swarr *et al.*, 2011).

LCA is standardized in the International Standards Organization (ISO) 14040 series. LCA is focused on explaining life cycle thinking related to the contributions of the chemical industry to identify negative and positive impacts throughout a product's entire lifespan. System boundaries of LCA consist of three types (Swarr *et al.*, 2011).

1. Cradle-to-gate

From raw material acquisition to factory gate

2. Cradle-to-grave

From raw material acquisition through product use and disposal

3. Gate-to-gate

From incoming raw materials in manufacturing to a finished product

2.4.2 Environmental Impact

Life Cycle Assessment (LCA) provides commonly used impacts. Some of these impacts are explained in more detail below to understand their definition (Swarr *et al.*, 2011).

Abiotic Depletion (fossil fuels)

Abiotic depletion of fossil fuels is a metric representing the amount of fossil fuels that are being reduced on earth. The resulting characterization factor unit for abiotic depletion of fossil fuels is presented in relation to 1 megajoule of the heating value of fossil fuels (MJ).

Acidification Potential

Acidification refers to processes that increase the hydrogen ion concentration [H+] of water and soil systems. Any change from the pH can have harmful effects on plant and aquatic life. The resulting characterization factor unit for acidification is presented in relation to 1 kilogram of SO_2 (kg SO_2 equivalent).

Eutrophication Potential

Eutrophication potential is also called nitrification potential defined as nutrient enrichment resulting in risen consumption and depletion of oxygen from the environment. The reference unit of eutrophication is expressed in equivalents of kilograms of phosphate (kg PO_4 equivalent).

Global Warming Potential

Global warming potential is a metric representing the adverse environmental effect caused by human emissions of greenhouse gases which result in an increase of the Earth’s surface temperature. Emissions of different gases are expressed in terms of a kilogram of carbon dioxide (kg CO_2 equivalent).

Human Toxicity

Ecotoxicity is a measure of the toxic impact that chemicals emitted by human activities impact on human health. The unit of the characterization factors used for ecotoxicity impact is expressed in term of kilograms of the toxic substance referred to 1,4-dichlorobenzene (kg 1,4-DB equivalent).

Photochemical Smog

Photochemical smog is an indicator of the potential adverse effects from the formation of low-level ozone and other photo-oxidants involving nitrogen oxides (NO_x) or volatile organic compounds (VOCs). Smog can adversely affect human health by causing respiratory illnesses. The reference unit used for photochemical oxidation is the equivalent of kilograms of ethylene. (kg C_2H_4).

Ozone Depletion

Ozone depletion refers to the destruction of stratospheric ozone. This layer of ozone is crucial to life because it absorbs ultraviolet radiation that affects human health and ecosystems severely. Chlorofluorocarbons (CFCs) is one of the major ozone-depleting substances that can decrease the concentration of ozone in the stratosphere resulting in the potential for less ultraviolet radiation to be absorbed. The reference unit is commonly expressed in terms of kilograms of CFC-11. (kg CFC-11 equivalent).

Allesch and coworker (2014) reviewed 151 studies which were involved with commonly used evaluation tools, namely, Cost-Benefit Analysis (CBA), Risk Assessment (RA), Life Cycle Assessment (LCA), Multi-Criteria-Decision-Making (MCDM) and Benchmarking to decision the most appropriate options for studied aspects. Table 2.17 was shown that LCA was the most used tool for evaluating environmental along with economic aspects. As mentioned previously, LCA is the most suitable evaluation tool in the study focusing on environmental issues.

Table 2.18 The percentage of reviewed studies in aspects (Allesch *et al.*, 2014)

Aspects	**Macro economics**	**Micro economics**	**Environment**	**Sociology**
CBA	67 %	19 %	95 %	43 %
RA	0 %	0 %	100 %	9 %
LCA	15 %	5 %	100 %	8 %
MCDM	60 %	33 %	93 %	60 %
Benchmarking	86 %	5 %	71 %	24 %

CHAPTER III
EXPERIMENTAL

3.1 Scope of Research

The scope of this research will cover the following:

1. The system boundary of the MFA and LCA model is conducted through end-of-life approach, starting from waste generation at the auto service and bus depot and also related-industrial activities to the waste processor after that the waste oils are treated or utilize, then the waste oils and by-product are disposed of by waste treatment options.
2. The amount of the waste oils is collected through site and literature survey and predicted from the published model regarding the number of vehicles registered in Bangkok.
3. The primary and secondary data, including the amount of wastes, waste route, the secondary product for materials, waste treatment options and emissions (e.g., solid waste, air pollution, wastewater) after waste disposal.
4. The contaminants focused in this study of the used lubricating oil are heavy metals (e.g., Pb, Cr, Zn, Cu) presented in substance level.
5. The LCA analysis is conducted through end-of-life approach using SimaPro software, and LCA methodology allows to determine environmental impacts based on Thailand database.
6. The used lubricating oil management scenarios are developed through waste management hierarchy, including (i) the worst case or the do-nothing option (ii) the current practice or the base case (iii) the simple distillation developed by DeMenno/Kerdoon (iv) the re-refining using Kinetics technology International (KTI) process and (v) the re-refining developed Revivoil process.
7. Environmental impact categories are composed of three categories, namely, global warming potential, abiotic depletion (fossil fuels) and human toxicity.

8. The functional unit is defined to be 1,000 kilograms of market demand of petroleum products in Thailand.

3.2 Methodology

This study was required software programs as shown below,

3.2.1 Software

1. STAN 2.6.801 developed by Technische Universität Wien
2. SimaPro 8.3.0
3. Microsoft Office 2016 (Excel)

3.2.2 Experimental Procedures

3.2.2.1 Define the scope and collect data in order to calculate the material balance

a. Set the scope and boundary systems for end-of-life of used lubricating oil scenarios.

b. Identify the characteristics and inventory of the processes in each scenario.

c. Collect the data inventory such as input and output of the production process, heat, electricity, or other information that involve the scenarios.

d. Calculate the mass balance of each scenario using STAN program as Material Flow Analysis (MFA) tool that helps to quantify flows and stocks of materials.

3.2.2.2 Classify wastes from used lubricating oil management and study impacts on environment with Life Cycle Assessment (LCA) procedures

a. Conduct inventory and classify the wastes occurred by the process in each scenario.

b. Define the disposal options and waste utilization based on the Department of Energy Business of Thailand and Department of Industrial Works of Thailand.

c. Input the data obtained from each scenario in SimaPro program.

d. Create impact categories that consist of three categories, namely, global warming potential, abiotic depletion (fossil fuels) and human toxicity.

3.2.2.3 Identify the appropriate scenario for used lubricating oil management

a. Evaluate and compare the effects of each scenario using the SimaPro results.

b. Identify the appropriate scenario with regard to environmental impacts and limitation on performance management

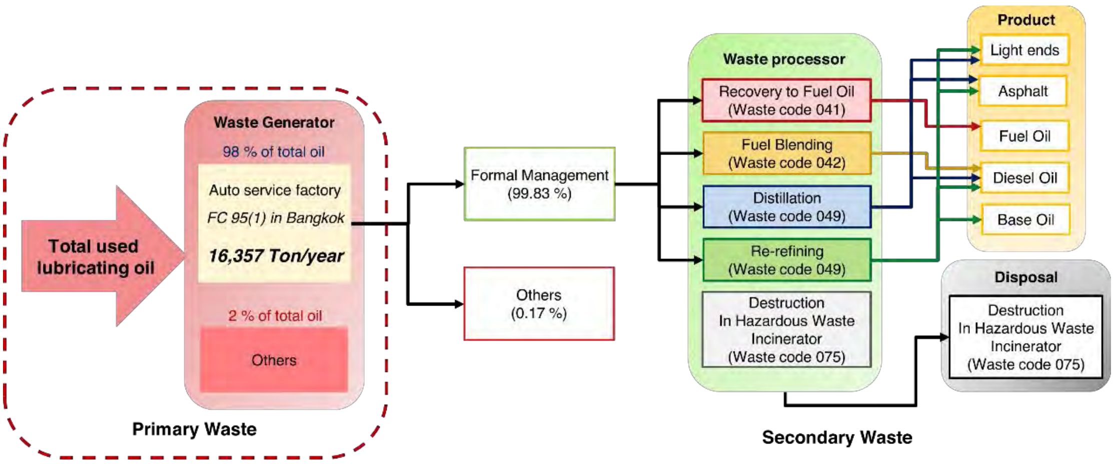


Figure 3.1 The system boundary of used lubricating oil management.

CHAPTER IV
RESULTS AND DISCUSSION

The MFA and LCA are useful tools for evaluating the environmental impacts of the used oil through its entire life cycle to employ the appropriate technology for sustainably used oil management. In this work, the end-of-life of used lubricating oil from the automotive sector was conducted. The system boundary of the used oil management was scoped in 4 main constraints.

1. Data of the used oil was collected from only waste generators reported to DIW (Sor Kor 2). The waste lubricating oil was selected from only factory code 95(1) in Bangkok, which is factory engaged with auto-services.
2. The selected waste code used in this study 13 02 08, which represents the waste oil from lubricants, accounted for about 98 % of the total waste oil from the factory code 95(1).
3. The distillation process selected in this study was waste oil distillation process developed by DeMenno/Kerdoon because the technology has been considered to be the leading recycler of waste oil that provides the long-term task on a commercial scale (Boughton *et al.*, 2004).
4. Re-refinery processes selected in this study was developed by Kinetics Technology International process (KTI) and Revivoil process. The reason is that KTI technology has been considered as an innovator of Thin Film Evaporation (TFE) technique offering the benefit of retaining the requisite properties of oil, and Revivoil process has been in desirable process economics and satisfactory operation making use of Thermal Deasphalting (TDA) process along with hydrotreating (Audibert, 2006).

The used oil data was obtained from the waste disposal report at the calendar year 2017 (DIW, 2017). The total average annual disposal of the used oil was 11.32 ton/site based on 1,445 auto service sites in Bangkok.

The waste flow of the used oils was created through the material balance knowledge using STAN version 2.6 software. The waste inventory was conducted and assessed the environmental impacts through LCA of each treatment scenario using SimaPro version 8.3.0. The CML-IA baseline V3.04/ EU25 method was used and the environmental impacts consisted of 3 categories indicated by mid-point level.

The waste treatment scenarios evaluated the base case (current practice), the extreme worst-case (do-nothing option), the extreme distillation developed by DeMenno/Kerdoon, the extreme KTI scenario and the extreme Revivoil scenario. The results of MFA and LCA of each scenario were compared and discussed in order to employ the appropriate technology for sustainably used lubricating oil management.

4.1 Waste Classification

Used lubricating oils mostly consist of lubricating oils and other oils, such as hydraulic oil, compressor oil and grease. Although the used oil can be used directly for fuel combustion, there is a limitation due to obsolete standard specifications in the used oil, e.g., sulfur, heavy metals, water, suspended solids and ashes.

From the survey data obtained from the study, the composition of the collected used oil was directly measured from 54 sites of the auto services in Thailand. About 14 sites (25.93 %) were located in Bangkok. As mentioned, Table 4.1 presents the number of auto services observed in the survey study in the calendar year 2015.

The properties of the used oil from the survey are shown in Table 4.2 and Table 4.3. It can be seen that the used lubricating oil contained several contaminants. The used oil consisted of 0.27 % of water content and 6.29 % of solid content including ash and suspended solids. According to the data shown in Table 2.6, it was noted that the standard specification of the used oil must require water content less than 0.05 % and solid content less than 0.07 %. For waste oil utilization, the heavy metals and sulfur level must be reduced as low as an acceptable level. Especially, lead is one of the most toxic substances. It should not be over 5 ppm for use as a fuel in engine and combustion in plants (Audibert, 2006). In the waste processing system, used lubricating oils must be sent to treatment for reducing the contaminant content to the desired level.

Table 4.1 The number of auto services observed from the survey study in 2015

No.	City	Total
1	Bangkok	14
2	Pathum Thani	4
3	Nonthaburi	6
4	Samut Prakan	3
5	Ayutthaya	4
6	Nakhon Pathom	4
7	Suphanburi	2
8	Kanchanaburi	2
9	Chachoengsao	3
10	Chonburi	5
11	Rayong	2
12	Chanthaburi	5

Note: Explanatory legend is shown below the table.

a) Northern region, Northeastern region and Southern region of Thailand was excluded in the survey.

Table 4.2 The average composition of the collected used lubricating oil (PPC, 2017)

No.	**Waste Type**	**Amount (wt%)**
1	Lubricating oil	86.01
2	Light naphtha	5.30
3	Gasoline	0.07
4	Diesel	1.32
5	Contaminated water	0.27
6	Sulfur	0.74
7	Heavy metals	< 0.01
8	Suspended solid	5.31
9	Ash	0.98
Total used lubricating oil		100.00

Table 4.3 The average composition of the heavy metals

No.	**Heavy Metal Type**	**Amount (ppm)**
1	Aluminum	4.90
2	Silicon	10.00
3	Iron	30.00
4	Lead	5.50
5	Chromium	1.20
6	Copper	4.10
7	Nickel	1.40
8	Tin	1.10
Heavy Metals		58.20

The waste disposal codes of the used lubricating oil regulated by the Department of Industrial Works (DIW) are divided into four codes as shown below

041 Recovery

042 Fuel blending

049 Recycling and Re-refinery

075 Hazardous waste incineration

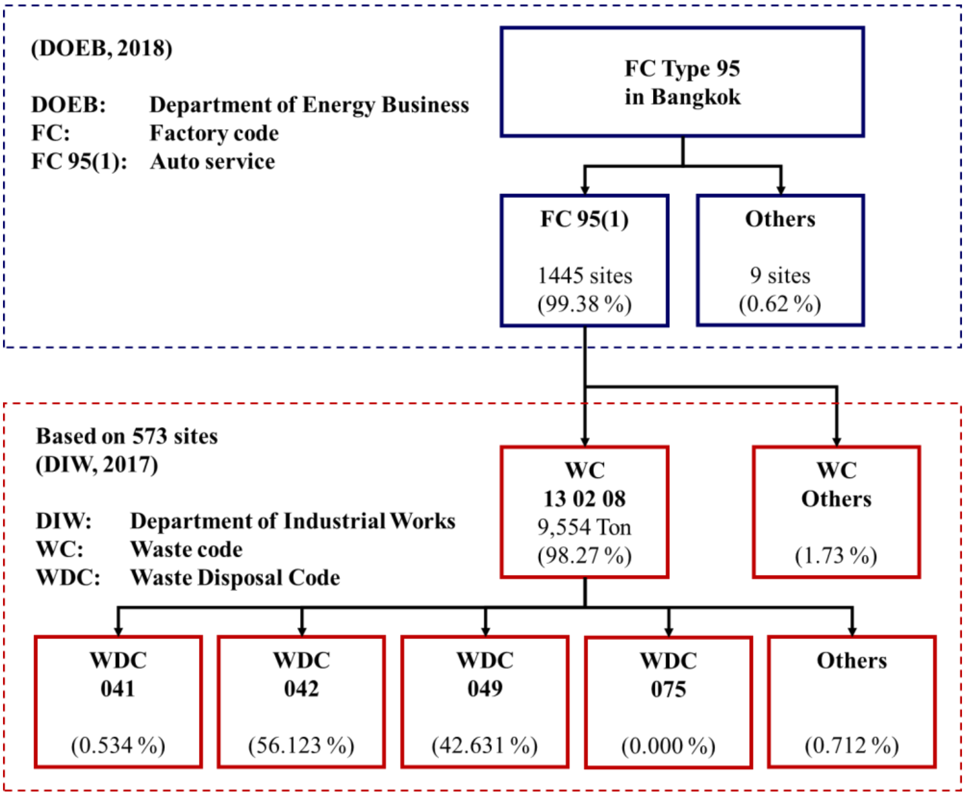


Figure 4.1 Flowchart of data selection for mass flow identification.

From Figure 4.1, the flowchart consisted of two different data sources. There were 1,445 sites of FC 95(1) located in Bangkok reported by the register. However, only 573 sites of them (39.65 %) reported the waste disposal code (WDC). It can be seen that fuel blending (WDC 042) was allocated the most fraction, followed by recycling and re-refinery (WDC 049), while hazardous waste incineration (WDC 075) was unallocated. According to the DIW report (2017), the used oils of 68 ton (0.712 %) could not specify their treatment option.

Table 4.4 The allocation of treatment method for the used lubricating oil management from 573 sites of auto services in Bangkok (DIW, 2017)

Waste Disposal Code (WDC)	**Amount (Ton)**	**Method allocation**
041 Recovery	51	0.54 %
042 Fuel blending	5,362	56.12 %
049 Recycling and Re-refinery	4,073	42.63[a] %
075 Hazardous waste incineration	0	0 %
Others	68	0.71[b] %
Total	**9,554**	**100 %**

Note: Explanatory legend is shown below the table.

a) The allocation ratio of recycling to re-refinery was assumed to be ratio 9:1 referred to California's base oil capacity (Kuczenski *et al.*, 2014).

b) Others were unspecified data.

From the survey study in 2015, the annual average disposal of used lubricating oil collected from auto service in Bangkok was about 11.32 ton per site. There were 1,445 sites of FC 95(1) in Bangkok. As mentioned, the result of multiplication between the average disposal of the used lubricating oil and the number of the sites of FC 95(1) from Bangkok was the total used lubricating oil obtained from the auto service located in Bangkok that was about 16,357 ton/year. With respect to the method allocation from Table 4.4, the total annual amount of used oil was allocated into various waste disposal codes as shown in Table 4.5.

Table 4.5 The allocation of treatment method for used lubricating oil management from 1,445 sites of auto services in Bangkok

Waste Disposal Code (WDC)	**Method allocation**	**Amount (Ton)**
041 Recovery	0.54 %	87
042 Fuel blending	56.12 %	9,180
049 Recycling and Re-refinery	42.63[a] %	6,973
075 Hazardous waste incineration	0 %	0
Others	0.71[b] %	117
Total	**100 %**	**16,357**

Table 4.6 The mass allocation of the output flows from recovery (WDC 041) (Kuczenski *et al.*, 2014)

Recovery	**Allocation percentage (weight %)**		
Waste Type	**Fuel Oil**	**Wastewater**	**Total**
Lubricating oil	93.10	6.90	**100.00**
Light naphtha	95.00	5.00	**100.00**
Gasoline	95.00	5.00	**100.00**
Diesel	95.00	5.00	**100.00**
Contaminated water	1.00	99.00	**100.00**
Sulfur	50.00	50.00	**100.00**
Heavy metals[d]	50.00	50.00	**100.00**
Suspended solid	50.00	50.00	**100.00**
Ash	50.00	50.00	**100.00**

Table 4.7 The mass allocation of the output flows from fuel blending (WDC 042) (Kuczenski *et al.*, 2014)

Fuel Blending	**Allocation percentage (weight %)**		
Waste Type	**Diesel[b]**	**Wastewater**	**Total**
Lubricating oil	99.90	0.10	**100.00**
Light naphtha	99.90	0.10	**100.00**
Gasoline	99.90	0.10	**100.00**
Diesel	99.90	0.10	**100.00**
Contaminated water	1.00	99.00	**100.00**
Sulfur	99.00	1.00	**100.00**
Heavy metals[d]	1.00	99.00	**100.00**
Suspended solid	0.05	99.95	**100.00**
Ash	1.00	99.00	**100.00**

Table 4.8 The mass allocation of the output flows from recycling (WDC 049) (Boughton *et al.*, 2004)

Recycling[a]	**Allocation percentage (weight %)**				
Waste Type	**Diesel[b]**	**Light ends[c]**	**Waste water**	**Asphalt**	**Total**
Lubricating oil	44.00	4.00	0.01	51.99	100.00
Light naphtha	0.89	99.00	0.01	0.10	100.00
Gasoline	0.89	99.00	0.01	0.10	100.00
Diesel	99.00	0.89	0.01	0.10	100.00
Contaminated water	0.10	0.80	99.00	0.10	100.00
Sulfur	0.10	0.89	0.01	99.00	100.00
Heavy metals[d]	10.00	10.00	10.00	70.00	100.00
Suspended solid	0.10	0.89	0.01	99.00	100.00
Ash	0.10	0.89	0.01	99.00	100.00

Note: Explanatory legend is expressed in Tables 4.6 - 4.8

a) Recycling of fossil fuels was known as distillation developed by DeMenno/Kerdoon Inc. (Boughton *et al*., 2004)

b) Diesel was classified as marine diesel oil.

c) Light ends were classified as gasoline.

d) The data of the heavy metals were referred to Table 4.3.

Table 4.9 The mass allocation of the output flows from re-refining developed by the Revivoil technology (WDC 049) (Audibert *et al*., 2006)

Re-refining	**Allocation percentage (weight %)**					
Waste Type	**Diesel**[a]	**Light ends**[b]	**Waste water**	**Asphalt**	**Base oil**[c]	**Total**
Lubricating oil	6.00	2.88	3.62	5.00	82.50	100.00
Light naphtha	0.25	99.00	0.25	0.25	0.25	100.00
Gasoline	0.25	99.00	0.25	0.25	0.25	100.00
Diesel	99.00	0.25	0.25	0.25	0.25	100.00
Contaminated water	0.00	0.00	100.00	0.00	0.00	100.00
Sulfur	0.25	0.25	0.00	16.35	83.15	100.00
Heavy metals[d]	0.00[e]	0.00[e]	0.00[e]	92.75	7.25	100.00
Suspended solid	0.25	0.25	0.25	99.00	0.25	100.00
Ash	0.00	0.00	0.00	90.91	9.09	100.00

Note: Explanatory legend is expressed below Table 4.9

a) Diesel was classified as marine diesel oil.

b) Light ends were classified as gasoline.

c) Base oil was composed of 15% weight of spindle oil, 50% weight of 200 SSU light base oil and 35% weight of bright stock.

d) The data of the heavy metals were referred to Table 4.3.

e) The allocation percentage in diesel, light ends and wastewater were not absolutely zero for the reason that heavy metals was measured at 10 ppm in their products.

Table 4.10 The mass allocation of the output flows from re-refining developed by the KTI technology (WDC 049) (Audibert et al., 2006)

Re-refining	**Allocation percentage (weight %)**					
Waste Type	**Diesel**[a]	**Light Ends**[b]	**Waste water**	**Base Oil**	**Fuel Oil**	**Total**
Lubricating oil	9.81	3.89	4.60	75.85	5.85	100.00
Light naphtha	0.25	99.00	0.25	0.25	0.25	100.00
Gasoline	0.25	99.00	0.25	0.25	0.25	100.00
Diesel	99.00	0.25	0.25	0.25	0.25	100.00
Contaminated water	0.00	0.00	100.00	0.00	0.00	100.00
Sulfur	0.58	0.58	0.00	98.26	0.58	100.00
Heavy metals[c]	0.00[d]	0.00[d]	0.00[d]	0.00[d]	100.00	100.00
Suspended solid	0.00	0.25	0.25	0.25	99.25	100.00
Ash	0.00	0.00	0.00	100.00	0.00	100.00

Note: Explanatory legend is expressed below Table 4.10

a) Diesel was classified as marine diesel oil.

b) Light ends were classified as gasoline.

c) The data of the heavy metals were referred to Table 4.3.

d) The allocation percentage in diesel, light ends and wastewater were not absolutely zero for the reason that heavy metals were measured at 4.4 ppm in their products.

4.2 Material Flow Analysis (MFA) of Base Case Scenario

The output flow of the used lubricating oil was conducted by substance flow using MFA software. The MFA can be used to express regarding the material balance of the waste stream and its treatment method (Brunner *et al.*, 2017). From Table 4.5, the total used lubricating oils obtained from the auto service located in Bangkok was estimated at 16,400 ton/year. From Table 4.2, the input flow of the used lubricating oil was separated into recovery (WDC 041), fuel blending (WDC 042), recycling (WDC 049), re-refinery by the Revivoil process (WDC 049) and other waste disposal options.

In this study, the waste flow started from the waste generator, i.e., auto service classified as FC 95(1). The waste flow was expressed in terms of the material balance starting from waste treatment options and finally towards through the output flow as the secondary products including the secondary wastes. According to Figure 4.2, the amount of the output flows by formal waste management in the calendar year 2017 was about 16,200 tons.

Each secondary product was calculated by the combination of each of the waste type in output flow, which was separately calculated by the result of multiplication between three parameters as shown below,

1. The average composition of the collected used lubricating oil as shown in Table 4.2
2. The total amount of the waste flows distributed to waste disposal codes (WDC) as shown in Table 4.5
3. The mass allocation of the output flows as shown in Tables 4.6-4.10

From Figure 4.2, the secondary products were distributed to diesel by 11,074 tons (67.71%), asphalt by 3,318 tons (20.28%), light ends by 609 tons (3.72%), base oils by 500 tons (3.06%) and fuel oils by 82 tons (0.5%), respectively. While wastewater classified as the secondary waste was about 657 tons (4.02%).

From Tables 2.5 to 2.9, the oil standard specification regulated by DOEB is that Low-Speed Diesel (LSD) must contain sulfur less than 1.5 %wt, ash less than 0.02 %wt and water including unknown solids less than 0.3 %wt. High-Speed Diesel (HSD) must contain sulfur less than 50 ppm, ash less than 0.01 %wt and water including unknown solids less than 0.05 %wt Then, gasoline must contain sulfur less than 50 ppm and water less than 0.7 %wt. Next, fuel oil must contain water including unknown solids less than 1.0 %wt and ash less than 0.1 %wt. After, base oil must considerably reduce water and solid content less than 0.05 %wt and 0.07 %wt. Finally, the wastewater must be contained sulfur less than 1 ppm, ash less than 50 ppm, contaminated petroleum products 5 ppm and heavy metals less than 4 ppm (Pollution Control Department PCD, 2017).

From Table 4.2, the contaminants were distributed in the secondary products. All of the secondary products contained the contaminants defined in the standard except for wastewater, thus the wastewater must be treated in the wastewater treatment facility before discharge to water resources. While the light ends should not be used for gasoline option due to the substandard of sulfur content that is less than 50 ppm. However, the light ends can function as naphtha for oil feedstock in the refinery. Furthermore, the diesel should not be used for high-speed diesel option due to the high-speed diesel standard that requires the sulfur content less than 50 ppm. The diesel is appropriate for low-speed diesel option because the low-speed diesel standard only requires the sulfur content less than 15,000 ppm.

According to Figures 4.3 to 4.6, the used lubricating oils consisted of valuable substances, i.e., lube oil, light naphtha, gasoline and diesel. Firstly, the lube oil was mainly distributed to the diesel product (73.81%), followed by the asphalt product (20.20%) and the base oil (3.40%). While, in fact, the base oil production was extremely low, the base oil was expected to be the main product due to its high value. As a consequence, to increase the base oil production, the allocation ratio of recycling to re-refinery need to be reduced. For the light naphtha and the gasoline, both were mainly distributed to the diesel product (56.82%), followed by the light ends (42.51%). Lastly, the diesel was mainly distributed to the diesel product (98.98%).

According to Figures 4.7 to 4.11, the used lubricating oils consisted of waste substances, i.e., contaminated water, sulfur, heavy metals, suspended solid and ash. Firstly, the sulfur contaminated the diesel product the most (73.81%), followed by the asphalt product (20.20%) and the base oil (3.40%). Secondly, the light naphtha and the gasoline were distributed to the diesel product the most (56.82%), followed by the light ends (42.51%). Thirdly, the diesel was distributed to the diesel product the most (98.98%)

Figure 4.2 The material flow diagram of total used lubricating oil from 1,445 sites of auto service in Bangkok (2017) (ton/year).

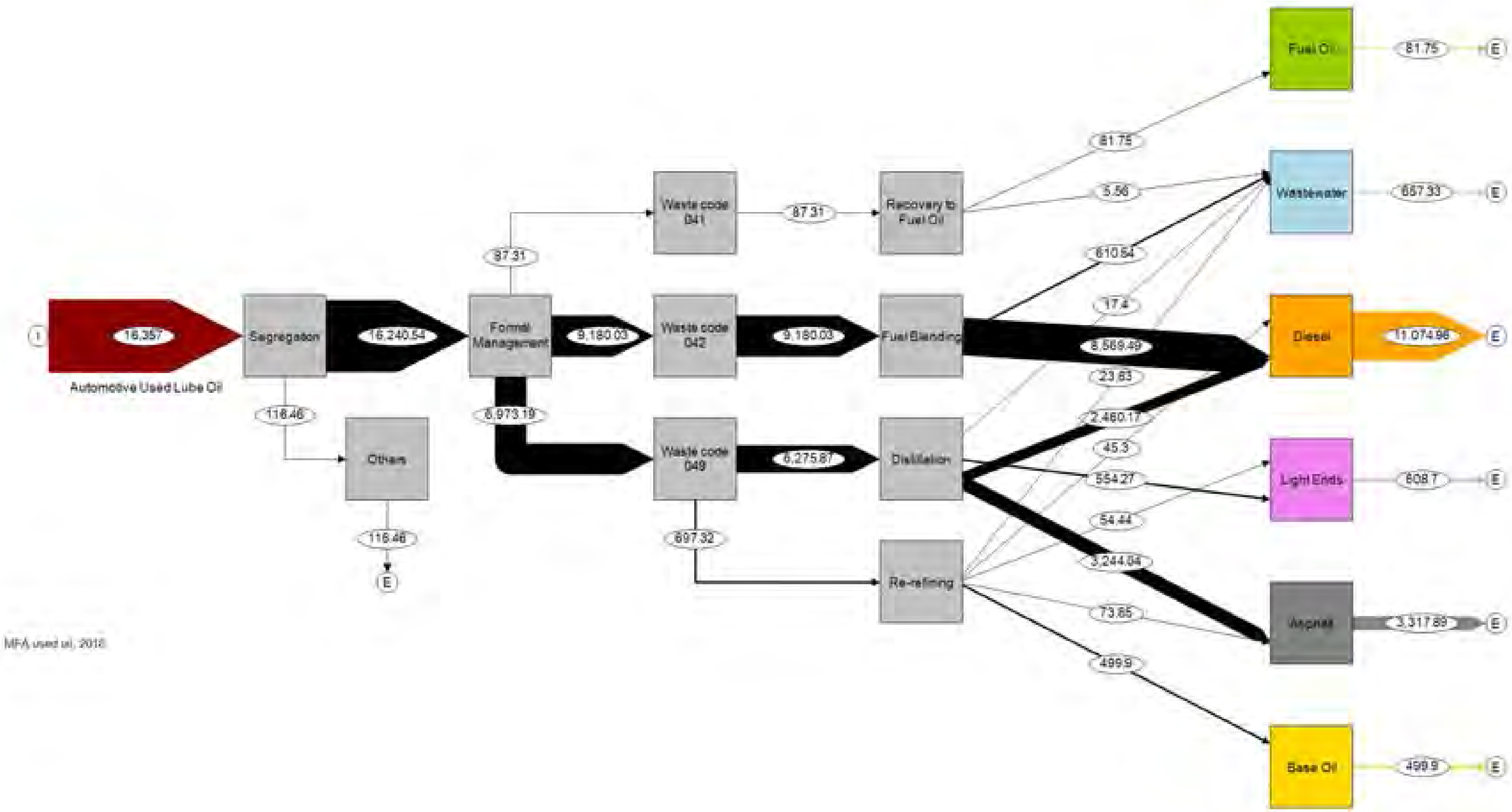


Table 4.11 Output flow composition of total used lubricating oil from 1,445 sites of auto service in Bangkok (2017) (ton/year).

Final product	**Diesel**		**Light Ends**		**Wastewater**		**Asphalt**		**Base Oil**		**Fuel Oil**	
Composition	**Wt%**	**Ton**	**Wt%**	**Ton**	**Wt%**	**Ton**	**Wt%**	**Ton**	**Wt%**	**Ton**	**Wt%**	**Ton**
Lube oil	92.99	10298.09	38.30	233.12	4.60	30.25	85.49	2836.45	98.98	494.78	91.77	75.02
Light Naphtha	4.42	489.11	60.11	365.88	0.09	0.62	0.01	0.43	0.02	0.09	5.65	4.62
Gasoline	0.06	6.37	0.78	4.76	0.00	0.01	0.00	0.01	0.00	0.00	0.07	0.06
Diesel	1.92	212.18	0.12	0.76	0.02	0.15	0.00	0.11	0.00	0.02	1.41	1.15
Contaminated water	0.00	0.26	0.02	0.14	6.61	43.42	0.00	0.02	0.00	0.00	0.01	0.01
Sulfur	0.61	67.31	0.07	0.43	0.11	0.69	1.41	46.82	0.86	4.29	0.78	0.64
Heavy metal	0.00	0.04	0.01	0.04	0.09	0.57	0.01	0.29	0.00	0.00	0.01	0.01
Suspended solid	0.01	0.67	0.50	3.06	74.81	491.75	11.05	366.57	0.02	0.09	0.28	0.23
Ash	0.01	0.96	0.09	0.55	13.68	89.92	2.02	67.10	0.12	0.62	0.01	0.01
Total	100.00	11074.99	100.00	608.74	100.00	657.37	100.00	3317.79	100.00	499.90	100.00	81.75

Figure 4.3 The material flow diagram of lube oil (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

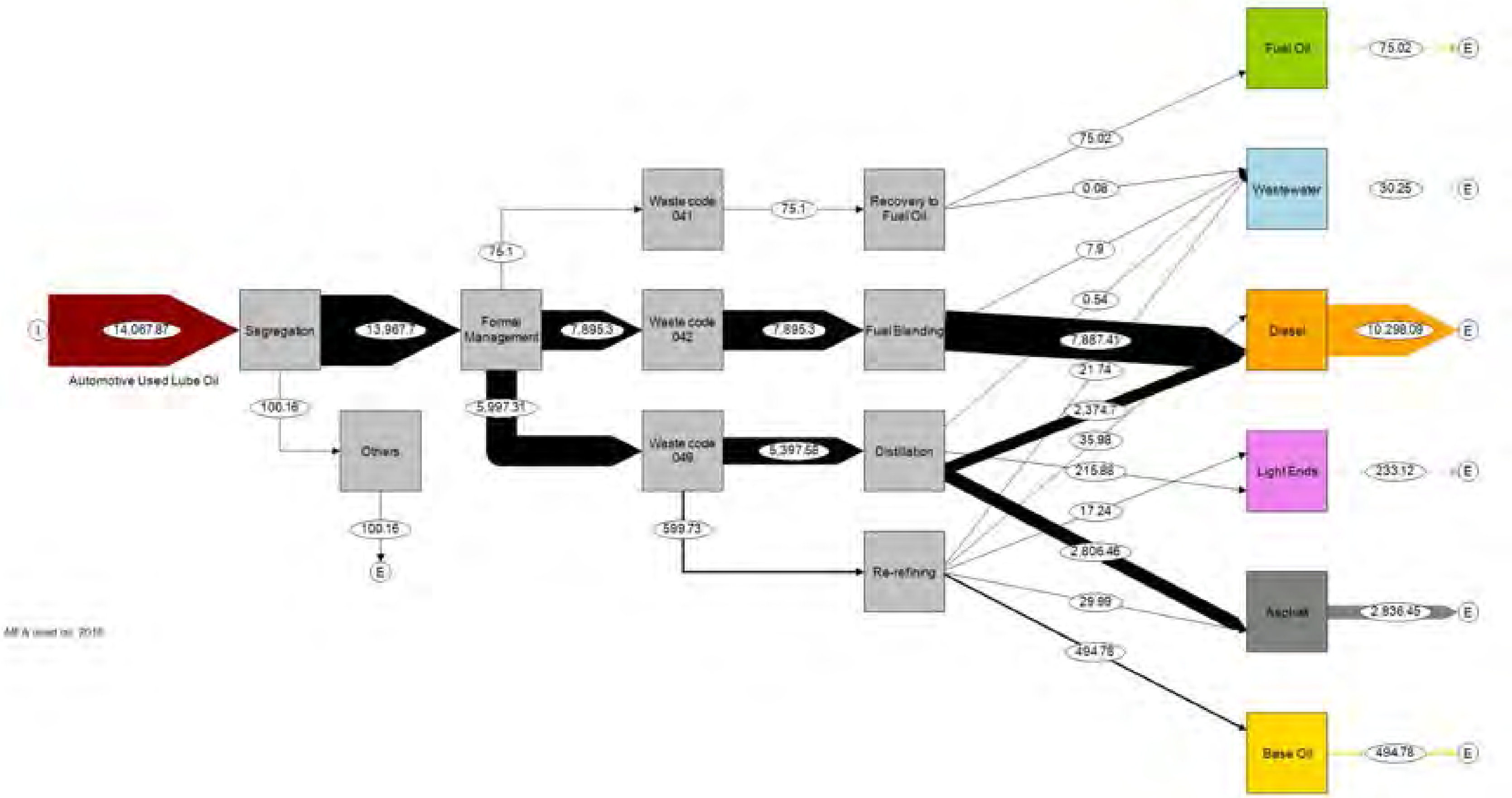


Figure 4.4 The material flow diagram of light naphtha (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

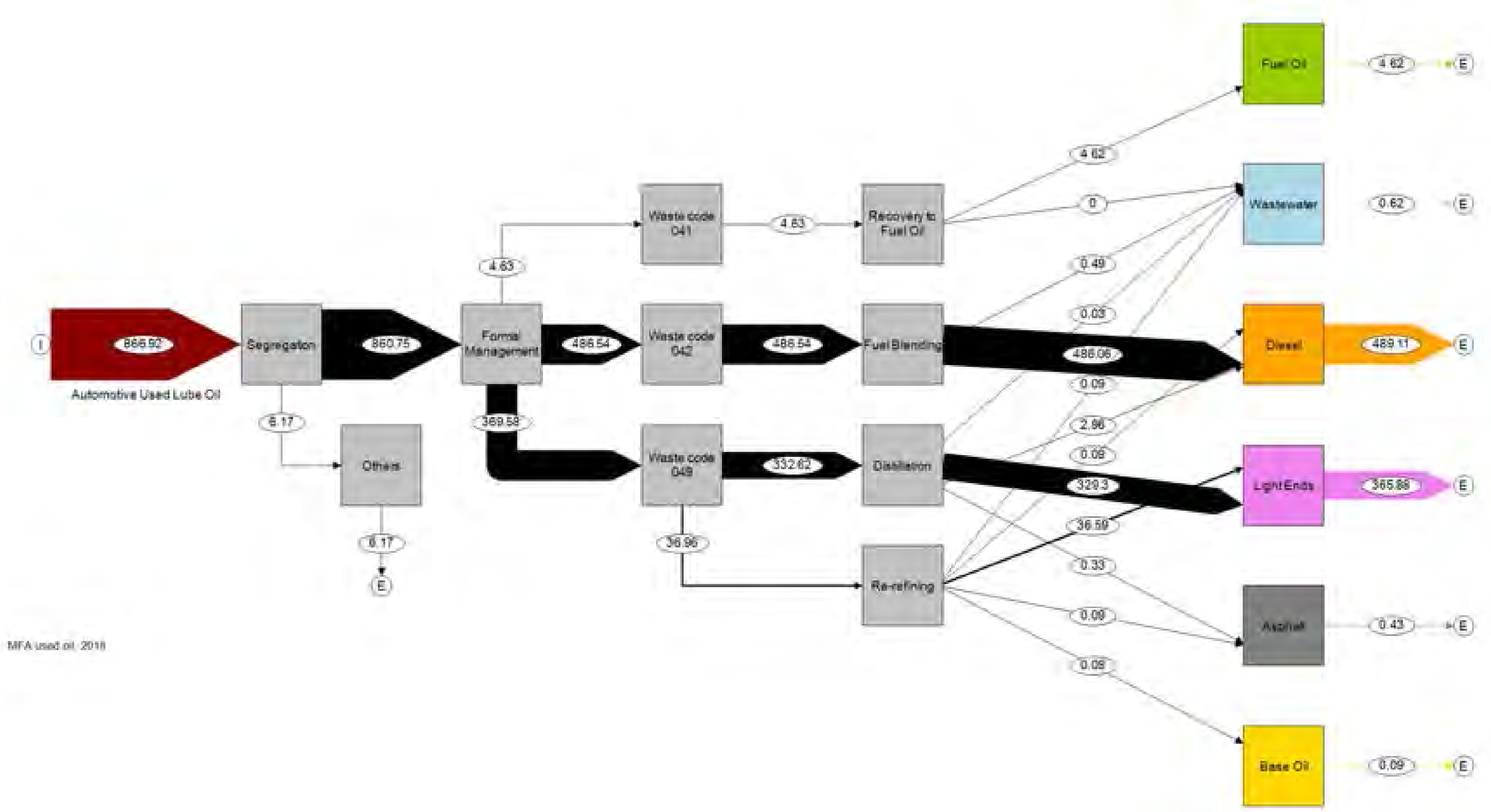


Figure 4.5 The material flow diagram of gasoline (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

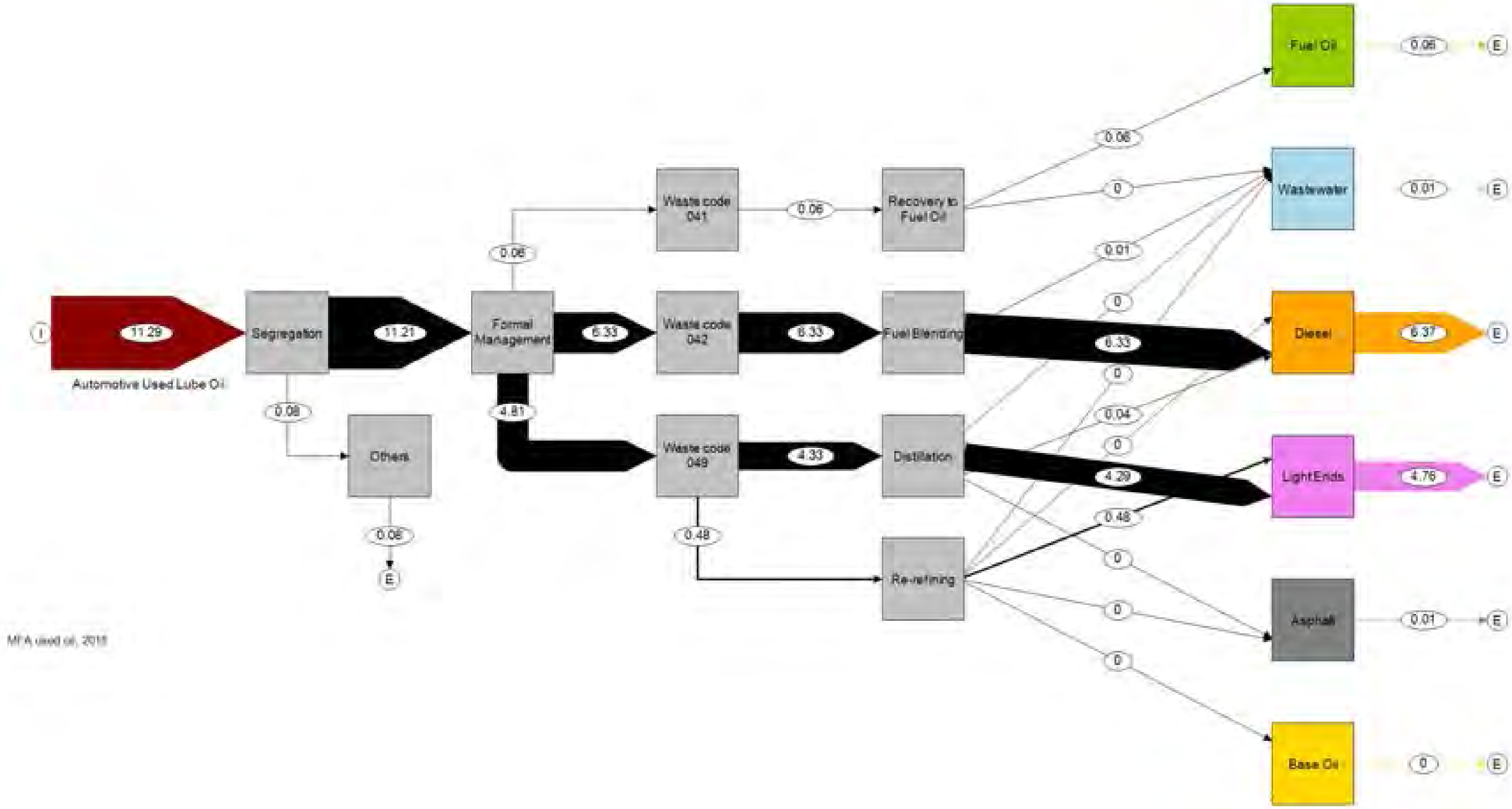


Figure 4.6 The material flow diagram of diesel (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

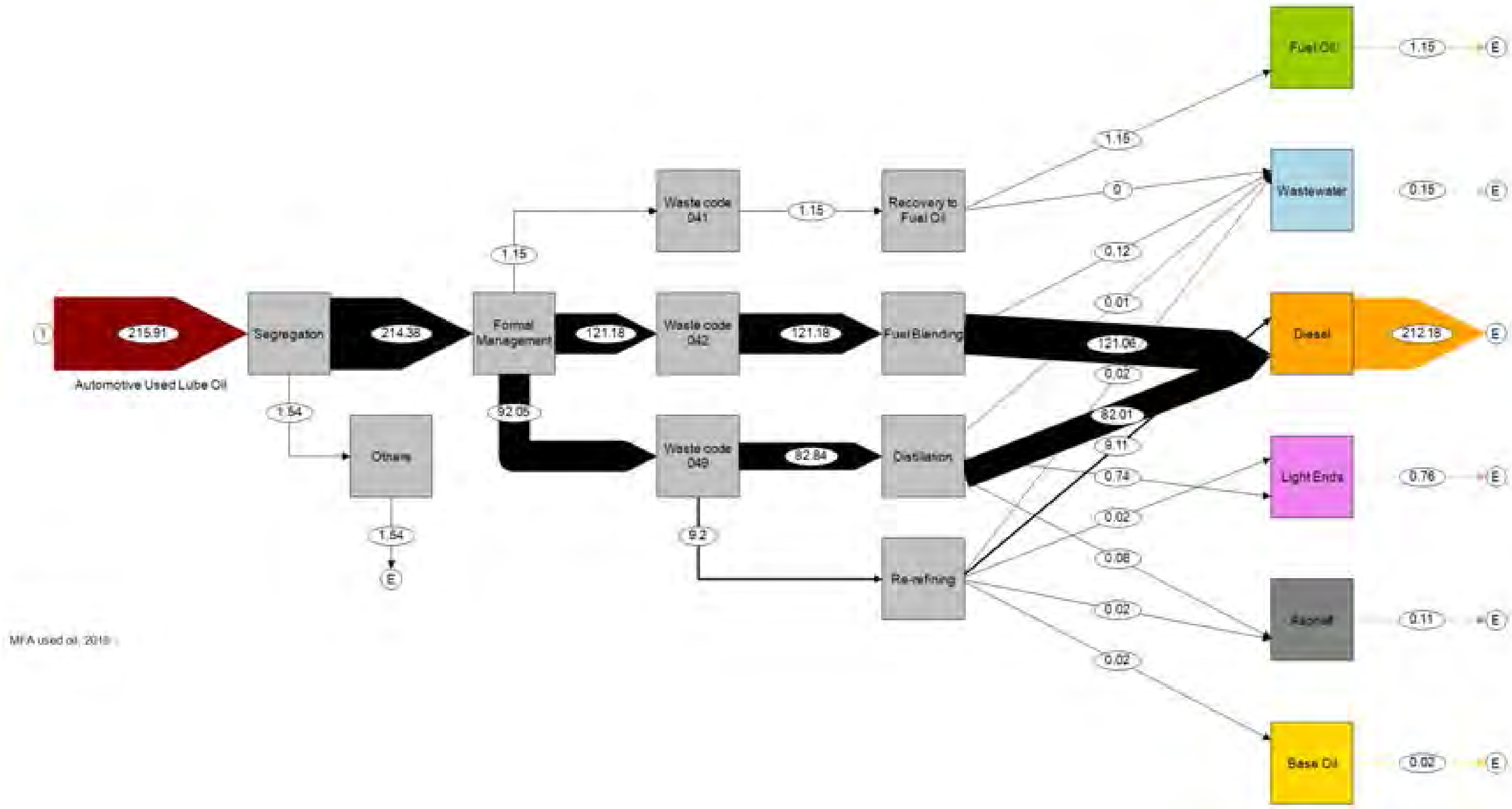


Figure 4.7 The material flow diagram of contaminated water (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

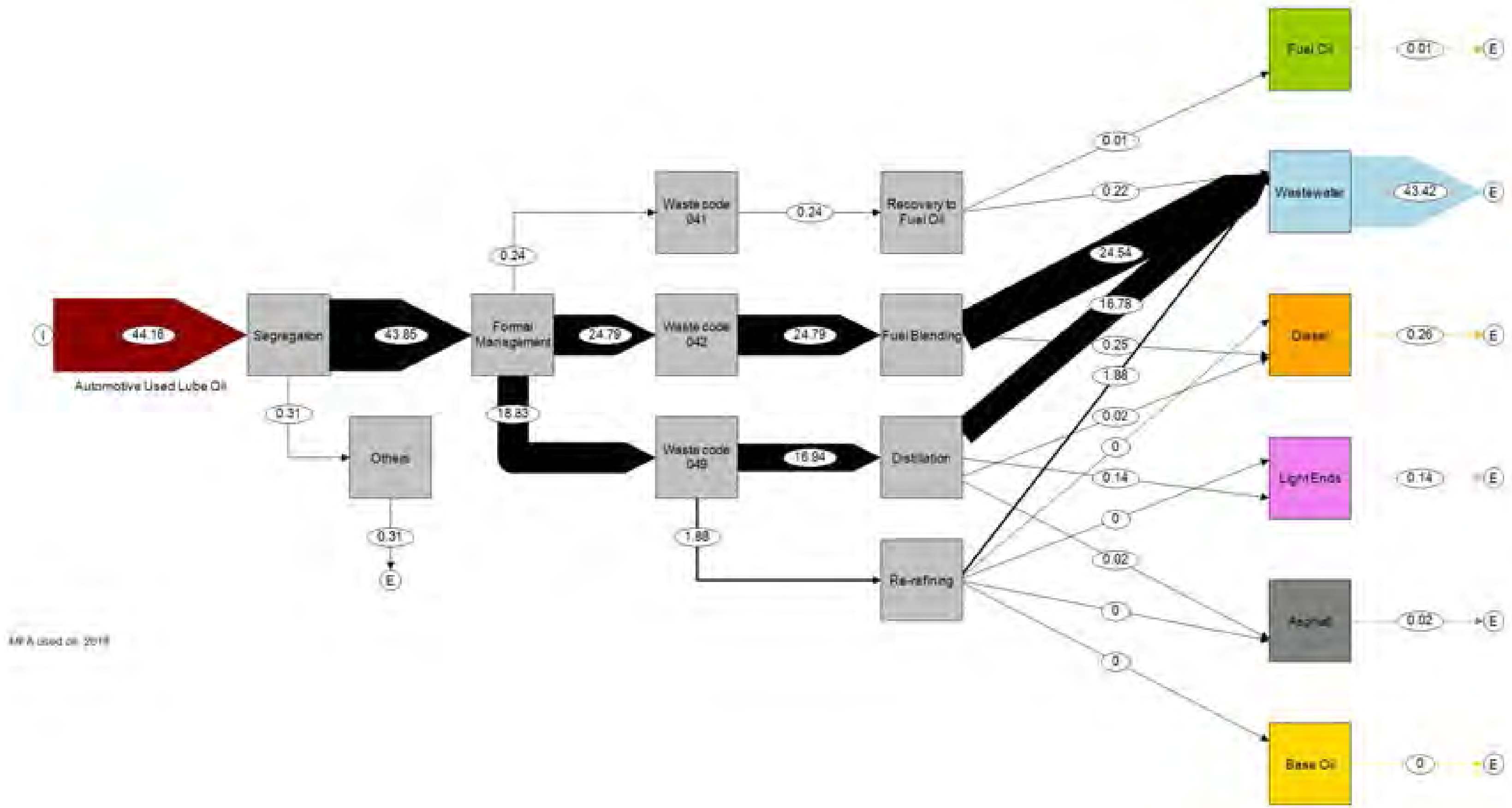


Figure 4.8 The material flow diagram of sulfur (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

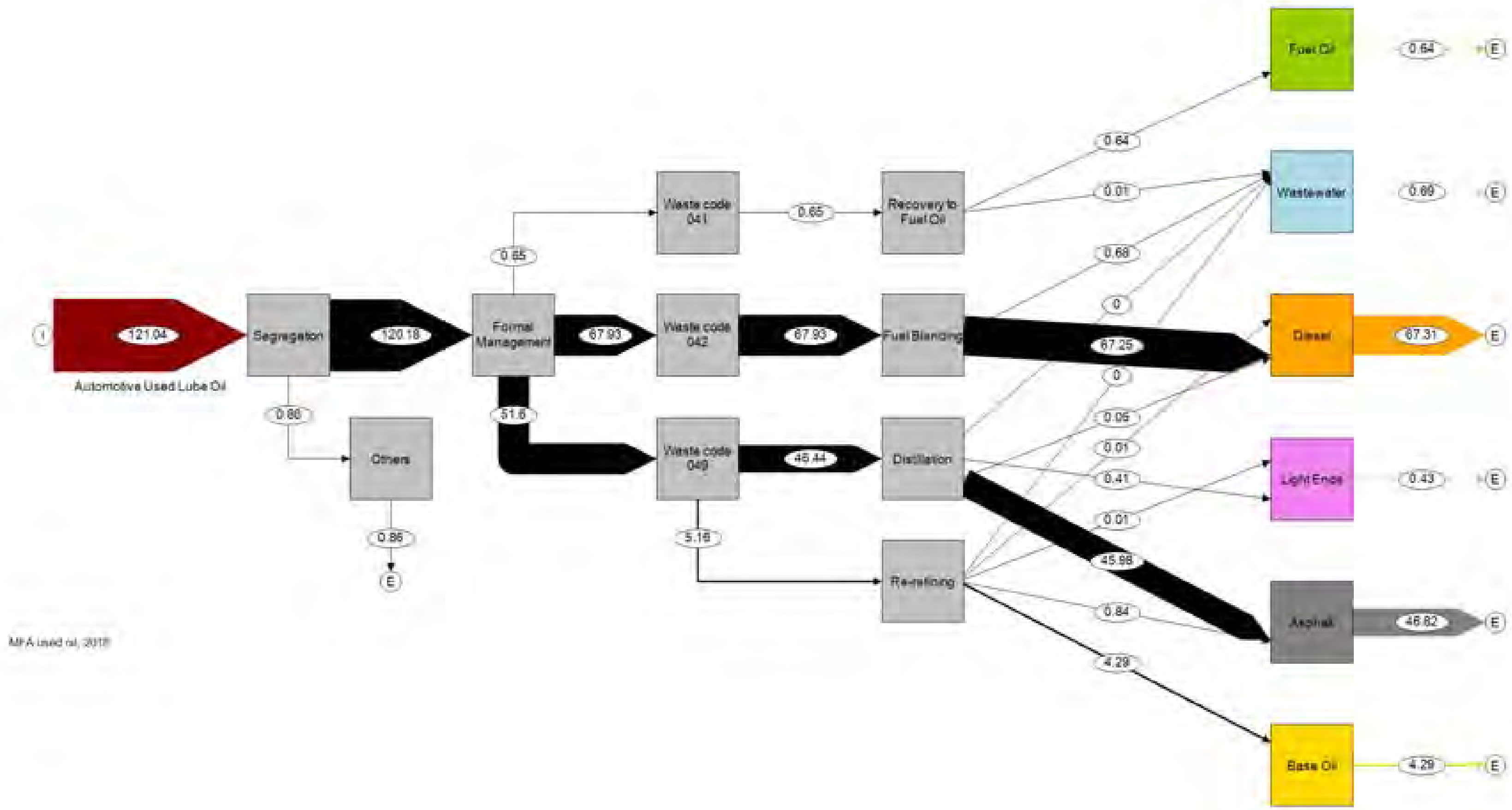


Figure 4.9 The material flow diagram of heavy metals (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

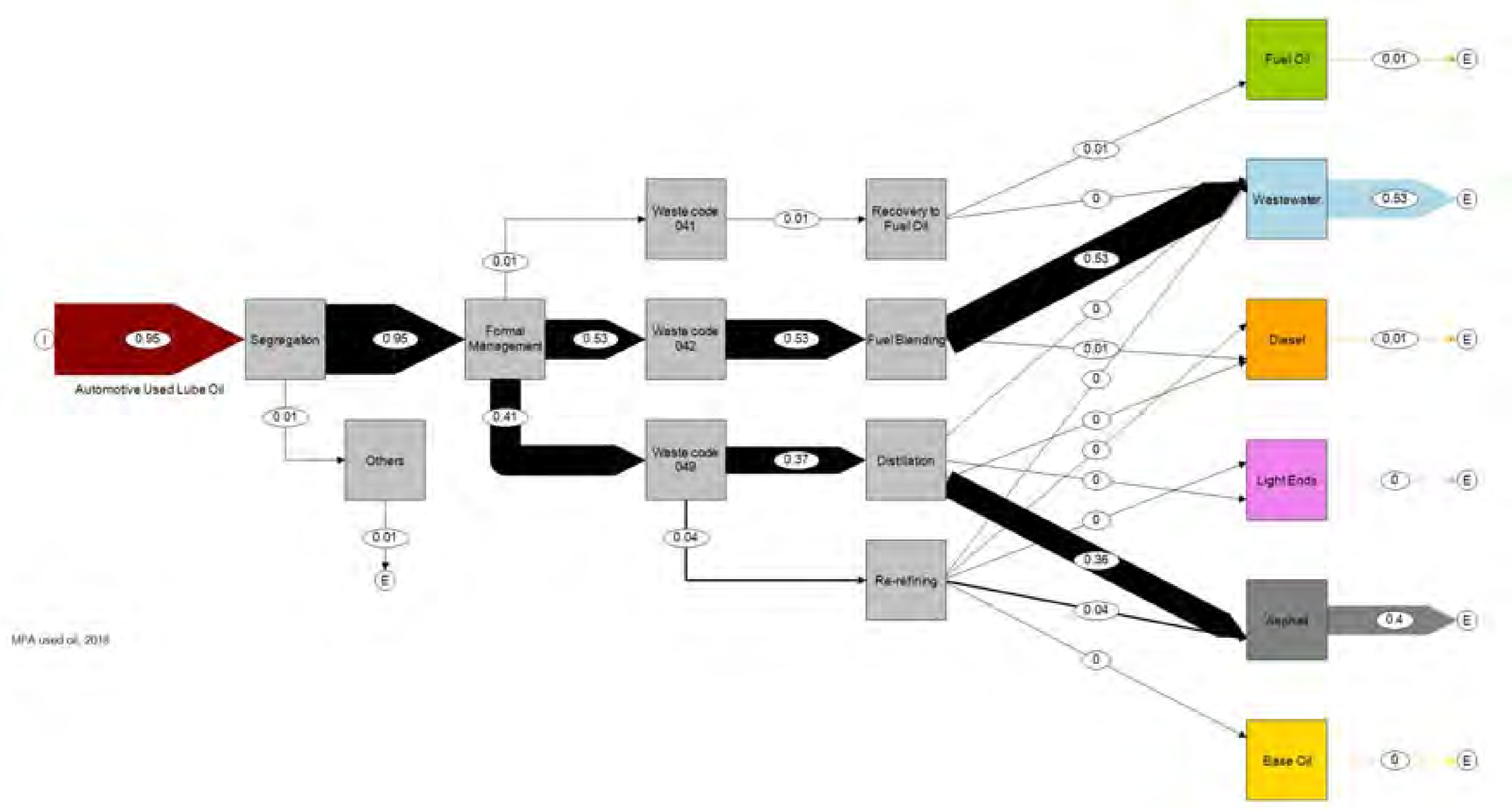


Figure 4.10 The material flow diagram of suspended solid (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).

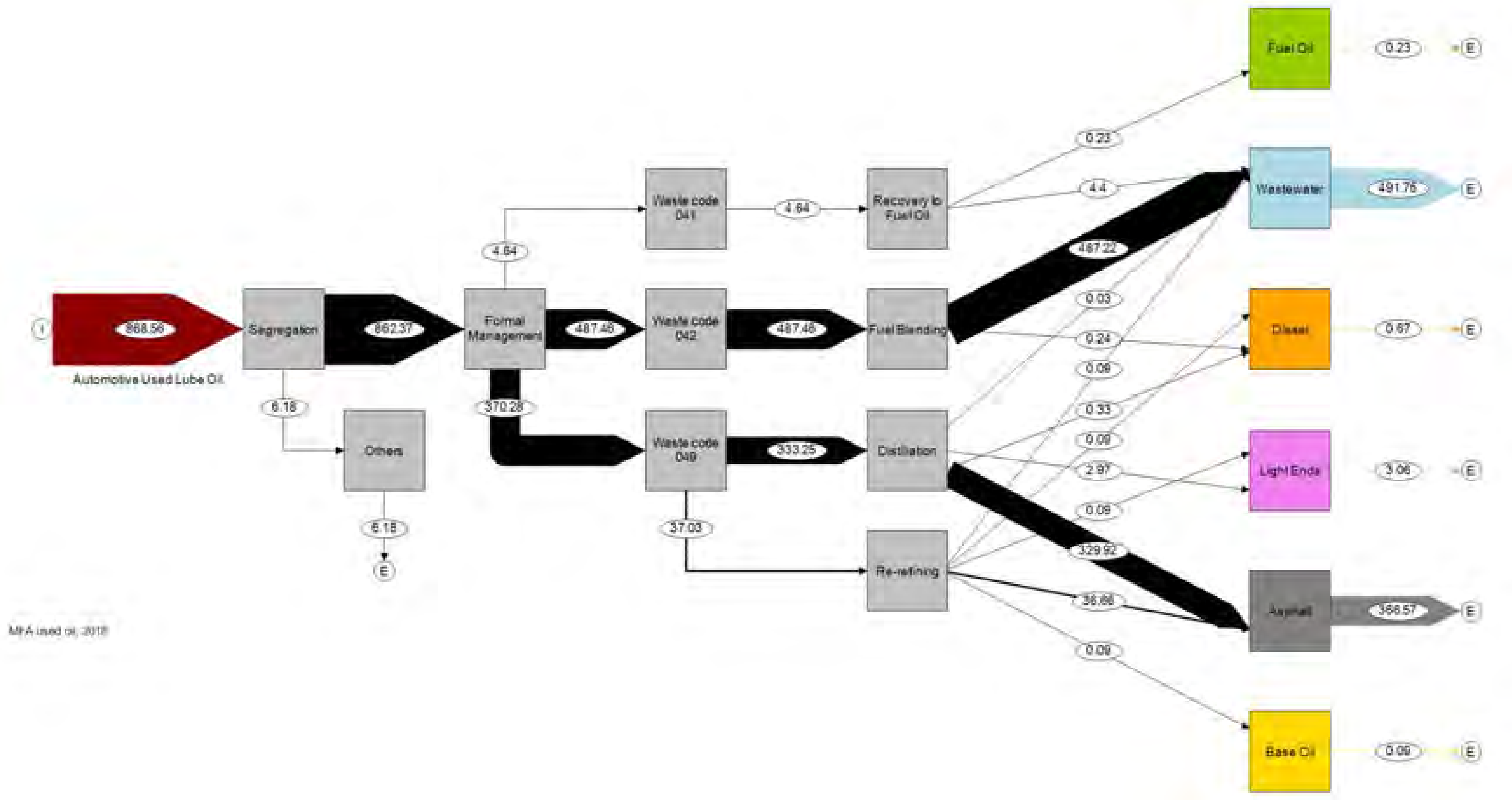
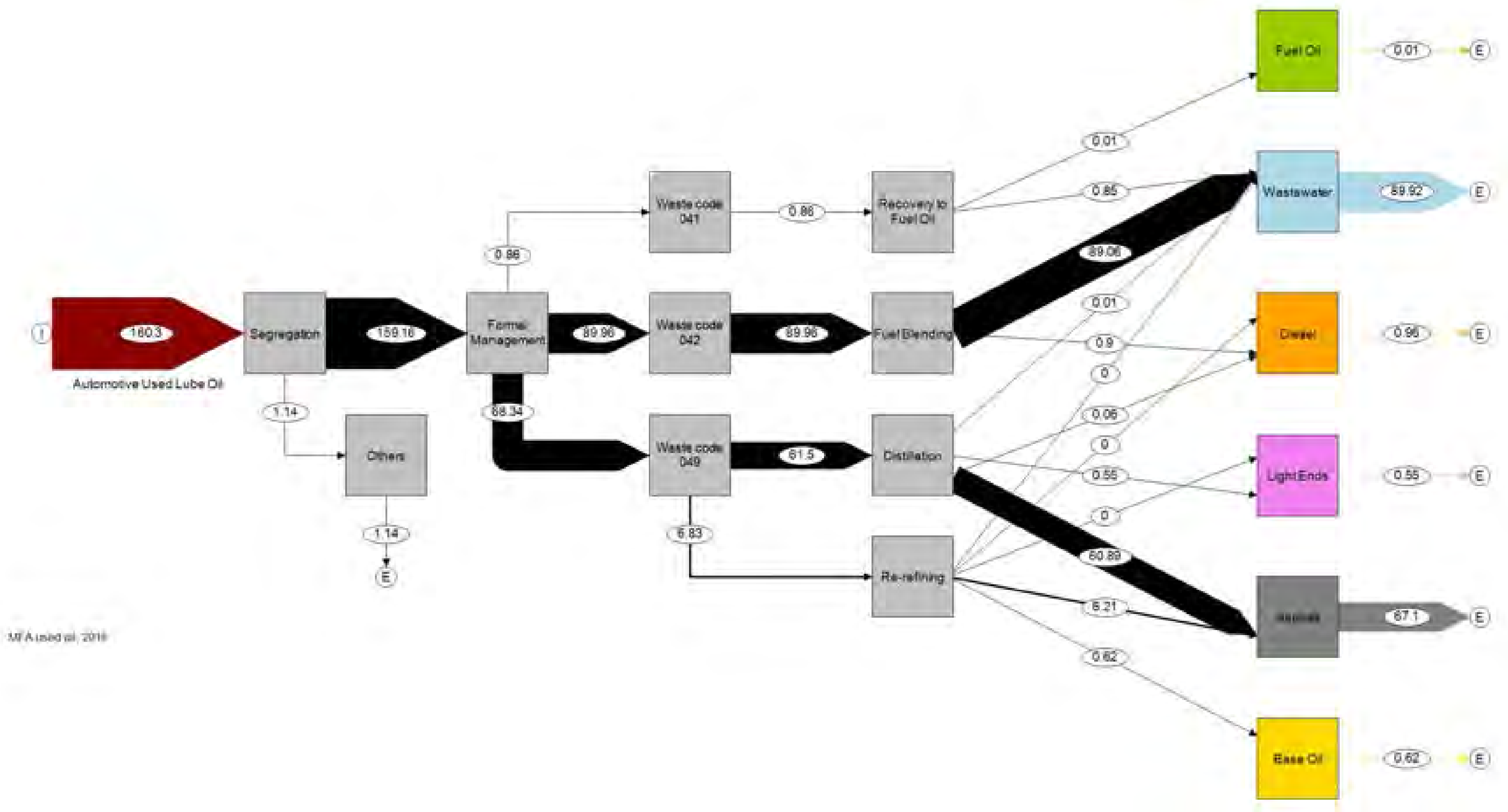


Figure 4.11 The material flow diagram of ash (sub-good) from 1,445 sites of auto service in Bangkok (2017) (ton/year).



4.3 Life Cycle Assessment (LCA) of Waste treatment option

Life Cycle Assessment is required to generate a quantitative environmental impact of the waste management of the used oil in order to provide necessary recommendations to promote waste management practice. In this study, the scenarios of waste management methods were developed into five options as shown below

Scenario 1: base case or current operation

the base case or current operation is the waste treatment option that all of the used oils were treated by recycling to produce a fuel oil as a main secondary product.

Scenario 2: zero-production

the zero-production is the waste treatment option that all of the used oils were treated by the hazardous waste incineration without transforming into secondary products.

Scenario 3: simple distillation or recycling

the simple distillation is the waste treatment option that all of the used oils were recycled by simple distillation developed by DeMenno/Kerdoon Inc (Boughton *et al.*, 2004). This process produced asphalt as a main secondary product with low-speed diesel as a co-product.

Scenario 4: KTI technology

the KTI is the waste treatment option that all of the used oils were treated by a re-refining process developed by KTI process (Audibert, 2006). This process enhanced product quality by the thin film evaporation process to produce a base oil as a main secondary product with low-speed diesel and fuel oil as co-products.

Scenario 5: Revivoil technology

the Revivoil is the waste treatment option that all of the used oils were treated by a re-refining process developed by Revivoil process (Audibert, 2006). This process improved product quality by the thermal deasphalting process to produce a base oil as a main secondary product with low-speed diesel and asphalt as co-products.

The functional unit in this study is defined to be a ton of Thailand's market demand of petroleum products in the calendar year 2017.

In this study, the five alternative scenarios of waste treatment of the used oil were calculated and evaluated their environmental impacts through SimaPro software version 8.3.0 by CML-IA V3.04/ EU25 impact assessment method, specifically for assessment of fossil fuel products. Therefore, the CML-IA was considered for the most recommended impact assessment method for used oil management due to containing the normalization and the characterization especially for Global Warming Potential (GWP), Depletion of fossil fuels and Human Toxicity, which were the most concerned impacts for petroleum refining related evaluation. The environmental impact categories in this method consist of three categories as shown below,

1) Global Warming; unit: kg CO_2 eq
2) Depletion of Fossil Fuels; unit: MJ
3) Human Toxicity; unit: kg 1,4 dichlorobenzene or kg 1,4-DB

Based on the current situation, Global Warming is a major concern due to the continued increase in global temperature since the 2010s (Prasad *et al.*, 2017). For the feasibility study expected, the LCA evaluation tool should combine with other evaluation tools, e.g., Cost-Benefit Analysis, Benchmarking, Multi-Criteria-Decision-Making and Risk Assessment (Allesch *et al.*, 2014).

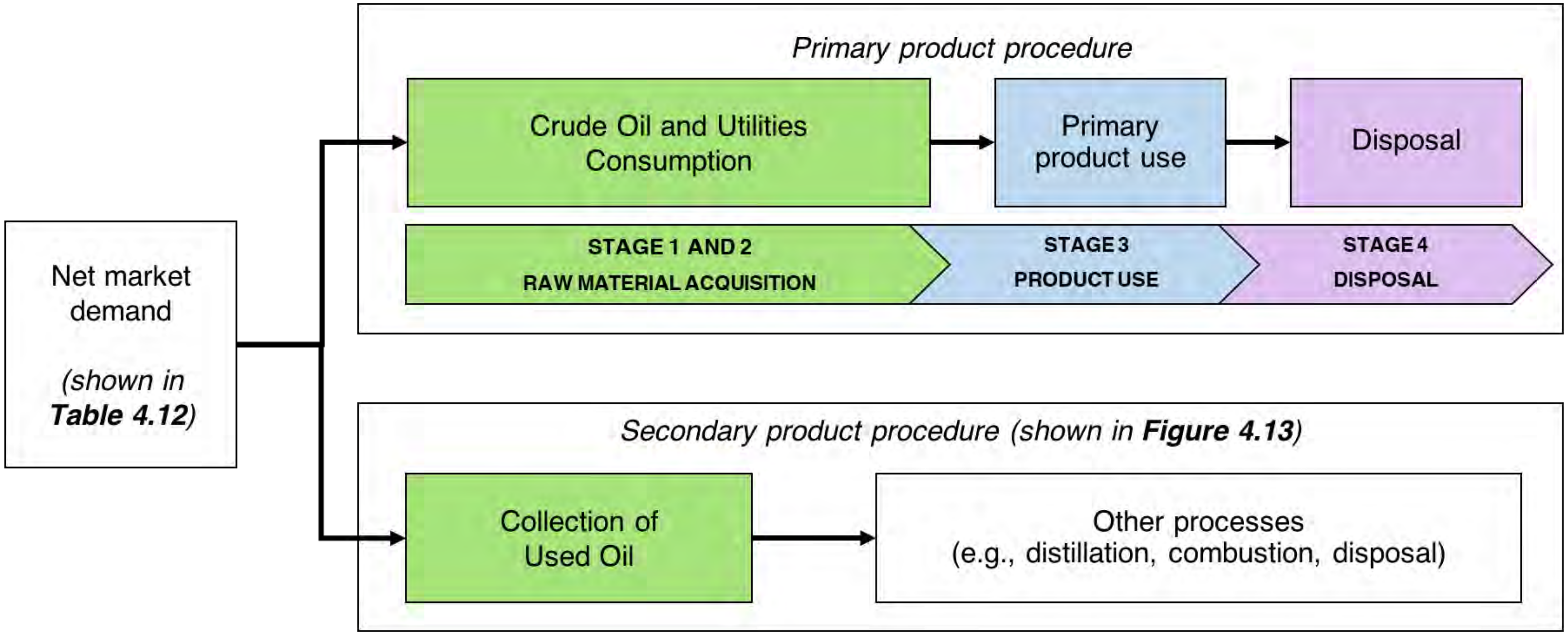
4.3.1 Scope

The studied system boundary is shown in Figure 4.12 that express the overall process flow diagram of the product route and Figure 4.13 that focus on the process flow diagram of the secondary product route. The diagram illustrated the procedure of waste management. The line style indicates the mass stream for each scenario. The system boundary was assumed that the mass flow through the system was independent time-series.

The following assumptions were excluded from the system boundary

1) Primary lubricating oil production
2) The primary use stage of lubricating oils before becoming used oil
3) The use and end-of-life of the re-refined base oil and asphalt
4) Transport, maintenance, and operation

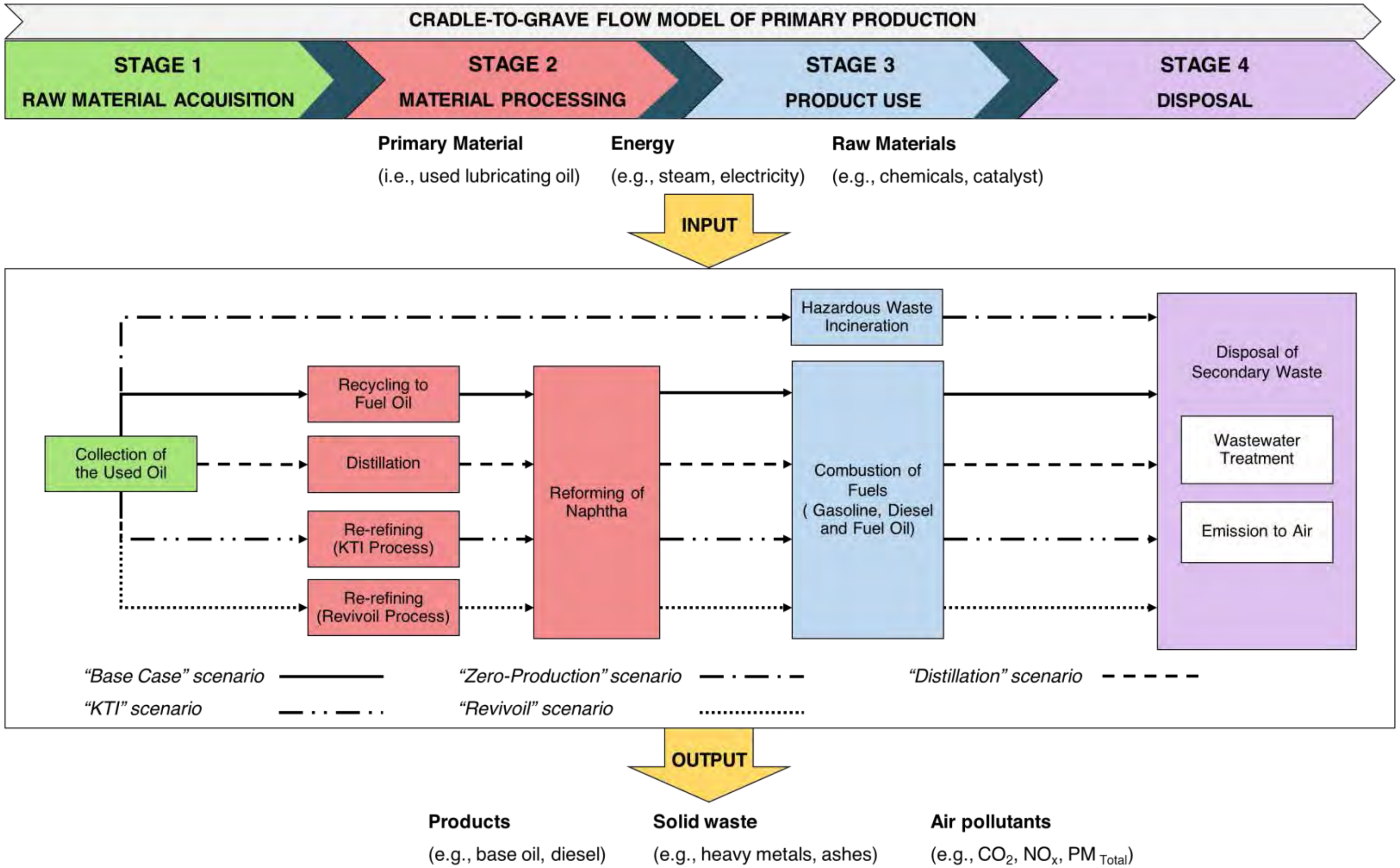
Figure 4.12 The overall system boundary of the used lubricating oil management.



Process flow defined in all scenarios

Note: The material processing (Stage 2) was combined with the raw material acquisition (Stage 1) in primary product procedure.

Figure 4.13 The system boundary of secondary product procedure from used lubricating oil.



From Figure 4.12, the overall process diagram illustrates the detail of the system boundary of the used lubricating oil management. The process started from the net market demand that was assumed to equate the net production. The net production was separated into primary and secondary product procedures. This process diagram focused on the primary product procedure, whereas the secondary product procedure was focused and explained in Figure 4.13.

The primary product procedure started from the raw material acquisition of crude oil extraction and their utilities, i.e., natural gas, electricity and water. These utilities were set in the material processing inventory. However, the material processing inventory was assumed to combine with the raw material acquisition inventory for simplified calculation. Finally, the waste generated through the entire processes must be disposed of by wastewater treatment and released as air emission. This assumption is applied to all scenarios.

Figure 4.13 shows the process diagram focused on the detail of the used oil management that becoming secondary products. Overall, there were four life cycle stages in the used lubricating oil management, started with the raw material acquisition and ended with the disposal.

First, the raw material acquisition was the first stage that involved withdrawing materials from the natural environment. In this study, this stage was related to the collection of the used oils from the auto services [FC 95(1)] in Bangkok. Products of the used oil management were assumed as the secondary products that displaced the comparable products in the current market. The surplus amount of secondary products was assumed to avoid the use of the primary product.

Next, material processing is the second stage that collects the used oil. It is arranged into five alternative routes as shown below,

1) Recycling to fuel oil route for the base case scenario
2) Distillation route for the distillation scenario
3) Re-refining (KTI process) for KTI scenario
4) Re-refining (Revivoil process) for Revivoil scenario
5) No production for the zero-production scenario

Then, the product use is defined as the third stage that is the stage related to the use of the product by combustion except for the zero-production scenario, which is conducted in hazardous waste incinerator. All scenarios have conducted with the uses of primary and secondary products in combustion. In this stage, the products were included gasoline, diesel and fuel oil, whereas asphalt and base oil were excluded. Finally, the disposal was the last stage that was divided into the wastewater treatment before the emissions to water resources and the emissions of gaseous to air.

4.3.2 Inventory design and life cycle stages

The LCA inventory followed though end-of-life of the used oil. Life cycle stage consisted of four stages for the impact assessment as shown below,

Stage 1 The raw material acquisition

Stage 2 The material processing

Stage 3 The product use

Stage 4 The disposal

Each life cycle stage required the inventory data, e.g., raw material, chemical, utility consumption and other characteristics of raw materials, chemicals and products. In this study, the inventory data obtained secondary data sources including existing databases and literature because the primary data that collected by observation from the organization is unavailable to define.

Stage 1 The raw material acquisition

The raw material acquisition stage was defined as the first LCA stage related to the net market demand of the petroleum product. It was assumed to be equal with the net production of petroleum product. The net production was divided into primary production and secondary production.

The primary products were mainly derived from the crude oil that had to be extracted from natural resources, whereas the secondary products were mainly derived from the used oils that already existed and was no need for extraction. So, the amount of the secondary products was expected to reduce as the overall primary product for making less of the crude oil recovery and the process utilities. The inventory data in this stage was calculated based on a ton of oil market demand. The raw material was transformed into the products, i.e., gasoline, diesel, fuel oil, base oil, LPG and bitumen. Crude oil was the raw material in the primary production, and the used lubricating oil was the raw material in the secondary production. From Tables 4.13 to 4.17, the proportion of the primary and secondary production in each scenario was calculated by the summation between the primary and secondary production was equal to Thailand's net market demand as shown in Table 4.12.

Table 4.12 The average proportion of petroleum products from market demand in Thailand based on 1,000 kg of petroleum products since 2015-2018 (DOEB, 2018)

Petroleum product[a]	**Net market demand (kg)**
Gasoline	211
Diesel	491
Fuel oil	107
Base oil[b]	176
LPG[c]	12
Bitumen	3
Total	**1,000**

Note: Explanatory legend is expressed below Table 4.12

a) The quality of each petroleum product was assumed to be comparable.
b) Base oil included typical base oil, lubricant, wax, high quality kerosene and other unspecified oils.
c) LPG was imported from abroad.

Table 4.13 The proportion of productions in the base case scenario based on the functional unit (1,000 kg of oil market demand in Thailand)

Petroleum product	Primary production (kg)	Secondary production (kg)	Net market demand (kg)
Gasoline	211	0	211
Diesel	491	0	491
Fuel oil	**-792**	899	107
Base oil	176	0	176
LPG	12	0	12
Bitumen	3	0	3
Total	**101**	**899**	**1,000**

Table 4.14 The proportion of productions in the zero-production scenario based on the functional unit (1,000 kg of oil market demand in Thailand)

Petroleum product	Primary production (kg)	Secondary production (kg)	Net market demand (kg)
Gasoline	211	0	211
Diesel	491	0	491
Fuel oil	107	0	107
Base oil	176	0	176
LPG	12	0	12
Bitumen	3	0	3
Total	**1,000**	**0**	**1,000**

Table 4.15 The proportion of productions in the simple distillation scenario based on the functional unit (1,000 kg of oil market demand in Thailand)

Petroleum product	Primary production (kg)	Secondary production (kg)	Net market demand (kg)
Gasoline	123	88	211
Diesel	99	392	491
Fuel oil	107	0	107
Base oil	176	0	176
LPG	12	0	12
Bitumen	**-514**	517	3
Total	**3**	**997**	**1,000**

Table 4.16 The proportion of productions in KTI scenario based on the functional unit (1,000 kg of oil market demand in Thailand)

Petroleum product	Primary production (kg)	Secondary production (kg)	Net market demand (kg)
Gasoline	124	87	211
Diesel	393	98	491
Fuel oil	4	103	107
Base oil	**-494**	670	176
LPG	12	0	12
Bitumen	3	0	3
Total	**42**	**958**	**1,000**

Table 4.17 The proportion of productions in Revivoil scenario based on the functional unit (1,000 kg of oil market demand in Thailand)

Petroleum product	**Primary production (kg)**	**Secondary production (kg)**	**Net market demand (kg)**
Gasoline	133	78	211
Diesel	426	65	491
Fuel oil	107	0	107
Base oil	**-541**	717	176
LPG	12	0	12
Bitumen	**-103**	106	3
Total	**34**	**966**	**1,000**

Note: Explanatory legend is expressed below Tables 4.13-4.17

a) Data in Tables 4.13 to 4.17 were calculated in Appendix A.
b) The negative value indicates the value of the surplus production without regarding to negative sign.
c) The positive value indicates the value of the necessary production.

For the primary production, the inventory of the raw material acquisition (Stage 1) was combined with the material processing (Stage 2) to simplify the calculation. The deficient production in each product was converted to the displaced products, i.e., crude oil, electricity, natural gas and water from the inventory parameters as shown in Table 4.18 before entering data in the inventory section, whereas the surplus production was available to directly enter data in the inventory section.

For the secondary production, the LCA inventory of the raw material acquisition (stage 1) was equal to zero because the used lubricating oil as the raw material was acquired without extraction from the natural resources. So, the data of the secondary production was unneeded for entering in SimaPro inventory.

Table 4.18 The inventory parameters of displaced products in the primary production (PE International, 2013)

Displaced products	Crude oil Unit: kg	Electricity Unit: MJ	Natural gas Unit: kg	Water Unit: kg
Gasoline (1kg)	1.11E+00	1.33E-01	5.61E-02	3.88E-01
Diesel (1kg)	1.11E+00	1.44E-01	4.77E-02	3.32E-01
Fuel oil (1kg)	9.79E-01	1.32E-01	5.07E-02	2.94E-01
Base oil (1kg)	1.08E+00	2.86E-01	1.13E-01	3.23E-01
Bitumen (1kg)	1.01E+00	5.27E-02	8.25E-03	3.03E-01

Note: Explanatory legend is expressed below Table 4.18

a) The inventory parameters were modeled in the combination of the raw material acquisition and the material processing stage for primary production.

Figure 4.14 shows the conceptual framework of in the raw material acquisition stage that separates into primary and secondary production route.

Figure 4.14 The framework of the raw material acquisition stage.

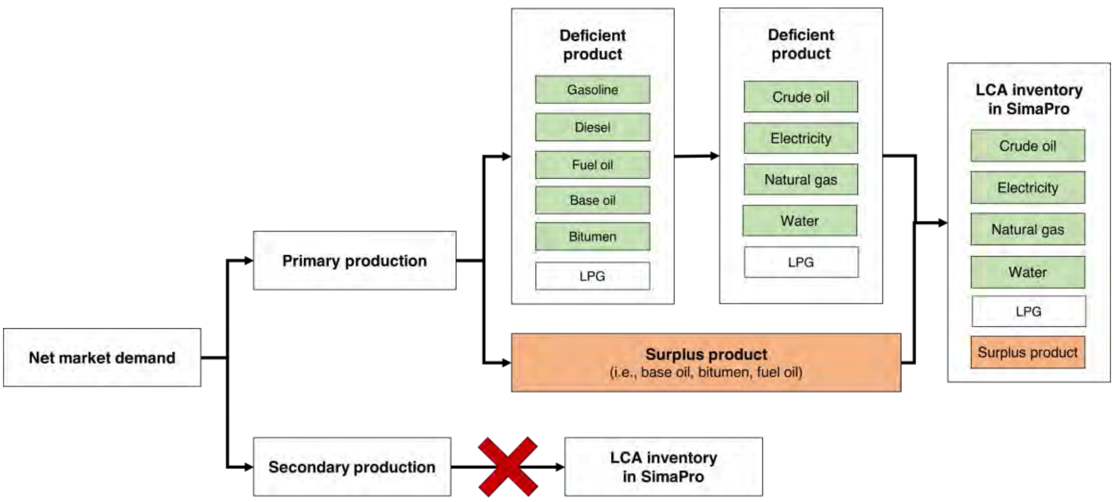


Table 4.19 The LCA inventory of the raw material acquisition stage (stage 1)

Input	Unit	Scenario 1 Base case	Scenario 2 Zero-production	Scenario 3 The distillation	Scenario 4 KTI process	Scenario 5 Revivoil process
Crude oil[a]	kg	973	1,078	541	582	726
Electricity[b]	MJ	149	163	95	74	93
Natural gas[c]	kg	55	61	37	26	33
Water[a]	kg	303	334	169	181	225
LPG[c]	kg	12	12	12	12	12
Surplus product[d]	**Unit**	**Scenario 1 Base case**	**Scenario 2 Zero-production**	**Scenario 3 The distillation**	**Scenario 4 KTI process**	**Scenario 5 Revivoil process**
Bitumen	kg	0	0	514	0	103
Base oil	kg	0	0	0	494	541
Fuel oil	kg	792	0	0	0	0

Note: Explanatory legend is expressed following Table 4.19

a) The inputs (i.e., crude oil and water) were entered in SimaPro inventory in the line “Known inputs from nature (resources)”
b) The input (i.e., electricity) was entered in SimaPro inventory in the line “Known inputs from technosphere (electricity and heat)”
c) The inputs (i.e., natural gas and LPG) were entered in SimaPro inventory in the line “Known inputs from technosphere (materials and fuels)”
d) The surplus product (i.e., bitumen, base oil and fuel oil) were entered in SimaPro inventory in the line “Known outputs to technosphere - avoided products”

For the raw material acquisition stage of primary production, The LCA inventory is expressed in Table 4.19. The inventory data consisted of the input inventory and the surplus product inventory. The calculation of the inventory data was shown in Appendix B. The input data consisted of LPG and the displaced products including crude oil, electricity natural gas and water. The LPG and natural gas were different between them. The LPG was mentioned as Thailand’s market demand. The LPG was not generated by the entire process, but extracted and imported from abroad, whereas the natural gas was one of the displaced products converted from Table 4.18. The surplus product inventory included bitumen, base oil and fuel oil, whereas the surplus product inventory excluded diesel, gasoline and LPG due to insufficiency products in Thailand’s market demand.

Stage 2 The material processing

The material processing stage was defined as the second LCA stage that related to chemicals, heat and utilities for production. The inventory of this stage is only considered as the secondary production because the material processing of the primary product was included in the raw material acquisition. The inventory data of the material processing in each scenario was expressed in Tables 4.20-4.23.

Firstly, the base case scenario was defined as a recycling of the used oil to fuel oil. The inventory data in the base case scenario is expressed in Table 4.20. Secondly, the zero-production was assumed that material processing is neglected, so there was no inventory data in this scenario. Thirdly, the simple distillation scenario has followed the process that developed by DeMenno/Kerdoon Inc. The inventory data in the simple distillation scenario is expressed in Table 4.21. Fourthly, KTI scenario was defined as the re-refining process developed by KTI technology. The inventory data in the simple distillation scenario is expressed in Table 4.22. Finally, Revivoil scenario was followed by the re-refining that developed by Revivoil technology. The inventory data in Revivoil scenario is expressed in Table 4.23.

For data entry, the inputs (i.e., heat, electricity and steam) were entered in SimaPro inventory in the electricity and heat section, whereas the other inputs (i.e., additives, chemicals and fuels) were accessed in SimaPro inventory in the materials and fuels section.

Table 4.20 The LCA inventory of the material processing in the base case scenario (Kuczenski *et al.*, 2014)

Base case scenario		
Process: Recycling to fuel oil		
Input	**Amount**	**Unit**
Heat[a]	54.05	MJ
Electricity[a]	838.3	MJ
Fuller's earth	18.00	kg
Sulfuric acid	9.000	kg

In addition, the simple distillation, KTI and Revivoil scenario was necessary to combine with the additional process (i.e., reforming light ends to gasoline) to ensure consistent quality of gasoline as the secondary product (Jean-François *et al.*, 2010). The inventory data was combined with the main process shown in Tables 4.21 to 4.23.

Table 4.21 The LCA inventory of the material processing in the simple distillation scenario (Boughton *et al.*, 2004)

Simple distillation scenario		
Process: Distillation (DeMenno/Kerdoon)		
Input	**Amount**	**Unit**
Sodium Chloride	3.10	kg
Natural gas	1,851.90	kg
Electricity[a]	89.50	kWh
Process: Reforming to gasoline[c]		
Input	**Amount**	**Unit**
Hydrogen[b]	6.15	kg
Electricity[a]	21.41	MJ
Heat[a]	127.60	MJ

Note: Explanatory legend is expressed below Tables 4.20-4.21

a) Heat and electricity were assumed to be produced by natural gas.
b) Hydrogen was especially for the reforming process.
c) Reforming required the feed of naphtha with a flow rate of 60,605 kg/hr (Jean-François *et al.*, 2010).

Table 4.22 The LCA inventory of the material processing in KTI scenario (Audibert, 2006)

KTI scenario		
Process: Re-refining (KTI technology)		
Input	**Amount**	**Unit**
Additives[a]	0.25	m^3
Water cooling[b]	2.00	m^3
Electricity[c]	94.00	kWh
Hydrogen[d]	2.42	kg
Nitrogen	1.60	m^3
Steam (7 bar)	26.50	kg
Process: Reforming to gasoline[f]		
Input	**Amount**	**Unit**
Hydrogen[e]	3.65	kg
Electricity[c]	12.72	MJ
Heat[c]	75.21	MJ

Note: Explanatory legend is expressed below Table 4.22

a) Additives were assumed to be unspecified.
b) Water cooling was originated from Thailand resources.
c) Heat and electricity were assumed to be produced by natural gas
d) Hydrogen was produced by diaphragm technology.
e) Hydrogen was especially for the reforming process.
f) Reforming required the feed of naphtha with a flow rate of 60,605 kg/hr (Jean-François *et al.*, 2010).

Table 4.23 The LCA inventory of the material processing in Revivoil scenario (Audibert, 2006)

Revivoil scenario		
Process: Re-refining (Revivoil technology)		
Input	**Amount**	**Unit**
Additives[a]	10.00	kg
Water cooling[b]	226.00	kg
Electricity[c]	55.00	kWh
Hydrogen[d]	2.50	kg
Steam	800.00	kg
Fuel oil[e]	65.00	kg
Catalyst[f]	0.25	kg
Process: Reforming to gasoline		
Input	**Amount**	**Unit**
Hydrogen[g]	1.65	kg
Electricity[c]	5.76	MJ
Heat[c]	34.05	MJ

Note: Explanatory legend is expressed below Table 4.23

a) Additives were assumed to be unspecified.
b) Water cooling is originated from Thailand resources.
c) Electricity and heat were assumed to be produced by natural gas
d) Hydrogen is produced by diaphragm technology.
e) Fuel oil was classified as heavy fuel oil generated from crude oil.
f) Catalyst in Revivoil process is a zeolite
g) Hydrogen is especially required for reforming process.
h) Reforming required the feed of naphtha with a flow rate of 60,605 kg/hr (Jean-François *et al.*, 2010).

Stage 3 The product use

The product use stage was defined as the third step of LCA stage that related to the utilization of the fuel by combustion of the used oil. The inventory data of the product use stage was developed by the combustion model for the simple distillation, KTI, and Revivoil scenario. The municipal solid waste incineration for the base case scenario and the hazardous waste incineration for the zero-production scenarios because the secondary products contained the contaminants (e.g., heavy metals, sulfur ,and ash) in the substandard level. (Johnke, 1992) The combustion model was designed a set of combustion emission factors for nine combustion pollutants, i.e., carbon dioxide (CO_2), methane (CH_4), dinitrogen monoxide (N_2O), carbon monoxide (CO), particulate matter (PM_{total}), nitrogen oxides (NO_x), sulfur oxides (SOx), Polycyclic Aromatic Hydrocarbons (PAH) and Non-Methane Volatile Organic Compounds (NMVOC) because the selected combustion pollutants were dependent on a fuel composition (Boughton *et al.*, 2004).

For the simple distillation, KTI and Revivoil scenario, the combustion emissions were assumed to be emitted to the atmosphere. The combustion model was calculated by the emission factors, which were divided into the combustion of primary products and the combustion of secondary products. The primary product was generated from crude oil, whereas the secondary product was generated from the used oil, so the characteristics of the primary product were different from the secondary product despite the same type of product. The products (i.e., gasoline, LPG, diesel and fuel oil) were included in this stage, but the base oil and asphalt were excluded from this stage due to being used for non-combustion activities. For the base case, the combustion emission factors were assumed to correspond to the emission factors of the municipal solid waste incineration (Johnke, 1992) because the characteristics of the products in the scenario were below the standard specifications regulated by DOEB. For the zero-production, the used oil was assumed to be directly treated by the hazardous waste incineration (WDC 075) without the material processing. The emission factors of hazardous waste incineration were conducted in this scenario (Johnke, 1992). As mentioned, the emission factor of the products was not measured directly but defined as the emission factor of the equivalent product represented in

Table 4.24. The emission factors of all pollutants except carbon dioxide (CO_2) were assumed to be the same value in all scenario, while the carbon emission was especially concentrated due to the most decisive influence on the environmental impacts, i.e., global warming potential, ozone depletion and fossil fuel depletion. Therefore, the emission factor of carbon dioxide was specially developed in the combustion model for the simple distillation, KTI and Revivoil scenarios; the municipal waste incineration for the base case scenario; and the hazardous waste incineration for the zero-production scenario. The carbon emission factors are shown in Table 4.25 for each scenario, and the emission factors of other pollutants are shown in Table 4.26.

Moreover, the energy released by combustion of fuels needed to be accessed in SimaPro inventory because the energy released is required for varied uses, e.g., production of electricity, industrial heating and cooking. For all scenarios, the energy released by combustion is equal to 34,865 MJ. The amount of energy released is calculated by the multiplication between the two parameters as shown below,

1. The calorific value of petroleum products (i.e., LPG, gasoline, diesel and fuel oil) is presented in Table 4.24
2. The average proportion of petroleum products from market demand (based on a ton of net market demand) is presented in Table 4.12.

Table 4.24 The relationship of equivalent product in the product use stage

Product[a]	Equivalent product		
	List	Calorific Value	Unit
Primary LPG	Natural gas	0.001	MJ/kg
Secondary LPG			
Primary gasoline	Gasoline	44	MJ/kg
Secondary gasoline			
Primary diesel	Distillate oil	43	MJ/kg
Secondary diesel	Marine distillate	43	MJ/kg
Primary fuel oil	Heavy fuel oil	41.4	MJ/kg
Secondary fuel oil	Recovery fuel oil	41.4	MJ/kg

For all pollutants, the combustion emission is shown in Table 4.27 and calculated by the multiplication between the two parameters as shown below,

1. The emission factor is presented in Table 4.25 for carbon dioxide and Table 4.26 for other pollutants, e.g., methane, carbon monoxide and sulfur oxides.
2. The primary and secondary production of the products (i.e., LPG, gasoline, diesel and fuel oil) in terms of mass are shown in Tables 4.13 - 4.17 that indicate for each scenario.

Table 4.25 The emission factors of carbon dioxide

<table>
<tr><th rowspan="2">Product</th><th colspan="5">Emission factor (kg CO_2 equivalent/ kg product use)</th></tr>
<tr><th>Scenario 1
Base case</th><th>Scenario 2
Zero-production</th><th>Scenario 3
Simple distillation</th><th>Scenario 4
KTI</th><th>Scenario 5
Revivoil</th></tr>
<tr><td>Primary LPG</td><td rowspan="2">8.75E-05</td><td rowspan="2">1.91E-04</td><td colspan="3" rowspan="2">5.50E-05</td></tr>
<tr><td>Secondary LPG</td></tr>
<tr><td>Primary gasoline</td><td rowspan="2">3.85E+00</td><td rowspan="2">8.40E+00</td><td colspan="3" rowspan="2">3.17E+00</td></tr>
<tr><td>Secondary gasoline</td></tr>
<tr><td>Primary diesel</td><td rowspan="2">3.76E+00</td><td rowspan="2">8.21E+00</td><td colspan="3">3.18E+00</td></tr>
<tr><td>Secondary diesel</td><td colspan="3">3.17E+00</td></tr>
<tr><td>Primary fuel oil</td><td rowspan="2">3.62E+00</td><td rowspan="2">7.90E+00</td><td colspan="3">3.27E+00</td></tr>
<tr><td>Secondary fuel oil</td><td colspan="3">2.98E+00</td></tr>
</table>

Note: Explanatory legend is expressed below Table 4.25

a) The emission factors of carbon dioxide equivalent in the base case and the zero-production scenario were defined as the waste incineration model (Johnke, 1992).
b) The emission factors of carbon dioxide equivalent in the simple distillation, KTI and Revivoil scenario were defined as the combustion model)Boughton *et al.*, 2004).

Table 4.26 The emission factors of other pollutants

Emission factor (kg/kg)[a]	**Pollutant**							
	CH_4	N_2O	CO	PM $_{Total}$	NO_x	SO_x	NMVOC	PAH
Primary LPG Secondary LPG	1.10E-09	1.10E-10	2.90E-09	6.50E-10	1.60E-08	3.50E-10	4.50E-09	2.90E-13
Primary gasoline Secondary gasoline	1.36E-04	2.77E-05	1.19E-03	9.68E-06	2.99E-03	1.72E-05	7.92E-05	4.84E-07
Primary diesel	1.38E-04	2.75E-05	1.42E-04	6.45E-05	1.59E-03	3.31E-03	6.02E-05	5.16E-07
Secondary diesel	1.59E-05	2.19E-04	3.01E-03	2.80E-03	4.00E-02	3.83E-03	1.59E-03	3.40E-05
Primary fuel oil	1.66E-05	2.28E-04	2.48E-03	1.66E-03	5.80E-02	7.04E-02	1.66E-04	3.48E-05
Secondary fuel oil	1.28E-04	2.53E-05	1.41E-04	2.40E-03	3.02E-03	7.45E-03	1.28E-04	7.87E-07

Note: Explanatory legend is expressed below (Table 4.26)

a) The unit of emission factor is defined as one kilogram of pollutant per one kilogram of product use.
b) The carbon emission factors were assumed to be defined as the combustion model (Boughton et al., 2004).

Table 4.27 The LCA inventory of the product use stage (stage 3)

No.	Pollutant	Emission factor (kg pollutant)				
		Scenario 1 Base case	Scenario 2 Zero-production	Scenario 3 Simple distillation	Scenario 4 KTI	Scenario 5 Revivoil
1	CO_2	3,882	6,656	2,584	2,554	2,584
2	CH_4	0[a]	0[a]	0[a]	0[a]	0[a]
3	N_2O	0[a]	0[a]	0[a]	0[a]	0[a]
4	CO	-2[b]	1	2	1	1
5	PM Total	1	0[a]	1	1	0[a]
6	NO_x	-42[b]	8	23	6	10
7	SO_x	-47[b]	9	9	3	9
8	NMVOC	0[a]	0[a]	1	0[a]	0[a]
9	PAH	0[a]	0[a]	0[a]	0[a]	0[a]

Note: Explanatory legend is expressed below;

a) The combustion emissions were not absolutely zero.
b) The set of negative sign value was defined as avoided emission.
c) The set of combustion emissions was entered in SimaPro in the section "Emissions to air".

Stage 4 The disposal

The disposal stage was defined as the End-of-life (EOL) of waste treatment. The inventory data of the disposal stage was assumed to be ended with the wastewater treatment (PE International, 2013) before the emissions discharge to water resources. From Tables 4.6 to 4.10, the wastewater was the undesired product generated through the entire process. The wastewater consisted of oil-contaminated water, heavy metals, sulfur, suspended solids and ashes. The set of the heavy metals, sulfur, suspended solids and ashes was directly available to enter in SimaPro inventory, whereas the wastewater was converted to the required materials in the wastewater treatment process before entering in SimaPro.

Table 4.28 The process inventory of wastewater treatment (PE International, 2013)

Process inventory for treatment of 1 kg used oil in wastewater		
Input	**Amount**	**Unit**
Electricity[a]	2.86E-03	MJ
Steam[b]	1.02E-01	MJ
Hydrated lime[c]	1.14E-03	Kg
Iron (II) chloride ($FeCl_2$)	5.71E-04	Kg
Phosphoric acid (H_3PO_4)	6.26E-08	Kg

Note: Explanatory legend is expressed below Table 4.28

a) Electricity is produced by natural gas.
b) Steam is produced by heavy fuel oil.
c) Limestone was entered as hydrated lime in the inventory.

For the zero production, the used lubricating oil was assumed to be classified as the wastewater because all of the used oil directly released into the water resources (Johnke, 1992), whereas the amounts of wastewater in other scenarios are shown in Tables 4.6-4.10. For the data set for the wastewater treatment (i.e., hydrated lime, electricity, steam, iron (II) chloride and phosphoric acid), the inventory of disposal stage (Table 4.29) is calculated by the multiplication between the inventory of wastewater treatment process (Table 4.28) and the amount of wastewater discharge in each scenario.

For the data set of the pollutants (i.e., sulfur, heavy metals, suspended solids), the data of disposal stage (Table 4.29) were assumed to be equal to the net amount of the pollutants in the products (i.e., wastewater, light ends, diesel, fuel oil) as shown in Tables 4.6 - 4.10. Whereas, the pollutants in base oil and asphalt were excluded due to leading a minor emission.

Table 4.29 The LCA inventory of the disposal stage (stage 4)

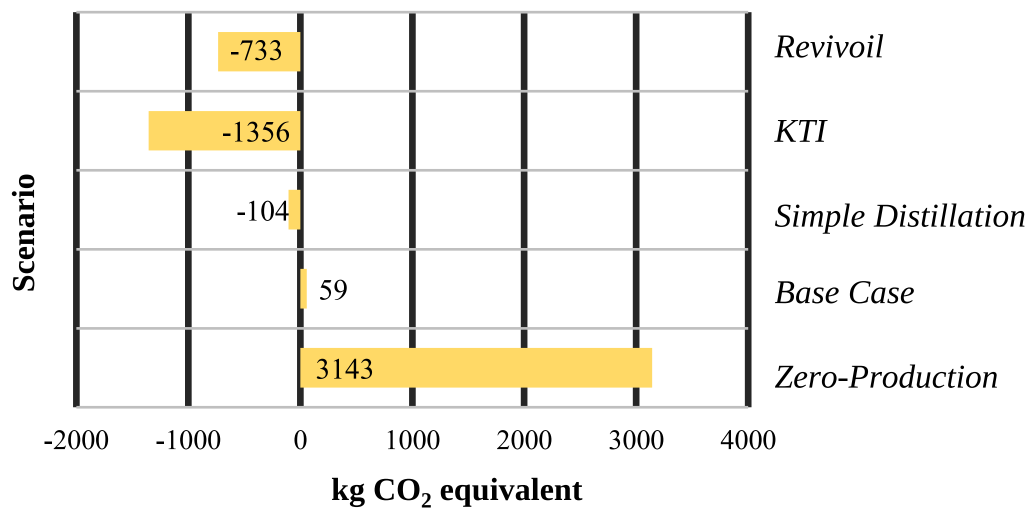
Input	Scenario 1 Base case	Scenario 2 Zero-production	Scenario 3 Simple distillation	Scenario 4 KTI	Scenario 5 Revivoil
Electricity (MJ)	2.87E-01	2.86E+00	7.94E-03	1.22E-01	9.77E-02
Steam (MJ)	1.03E+01	1.02E+02	2.84E-01	4.35E+00	3.49E+00
Hydrate lime (kg)	1.15E-01	1.14E+00	3.18E-03	4.87E-02	3.91E-02
Iron (II) chloride (kg)	5.74E-02	5.71E-01	1.59E-03	2.43E-02	1.95E-02
Phosphoric acid (kg)	6.29E-06	6.26E-05	1.74E-07	2.67E-06	2.14E-06
Sulfur (kg)	7.40E+00	7.40E+00	7.40E-02	1.29E-01	3.71E-02
Heavy metals (kg)	5.82E-02	5.82E-02	1.75E-02	5.82E-02	4.22E-03
Suspended solid[e] (kg)	6.29E+01	6.29E+01	6.29E-01	5.31E+01	1.42E+00

Note: Explanatory legend is expressed below;

a) Hydrated lime was assumed to be entered in SimaPro inventory in the section "Resources"
b) The set of wastewater treatment inventory except for hydrated lime (i.e., electricity, steam, iron (II) chloride and phosphoric acid was entered in SimaPro inventory in the line "Materials/fuels"
c) Suspended solid was assumed to be combined with ash.
d) The pollutants (i.e., sulfur, heavy metals and suspended solids) were assumed to be released to water resources.
e) The set of the pollutants was entered in SimaPro inventory in the section "Emissions to Water"

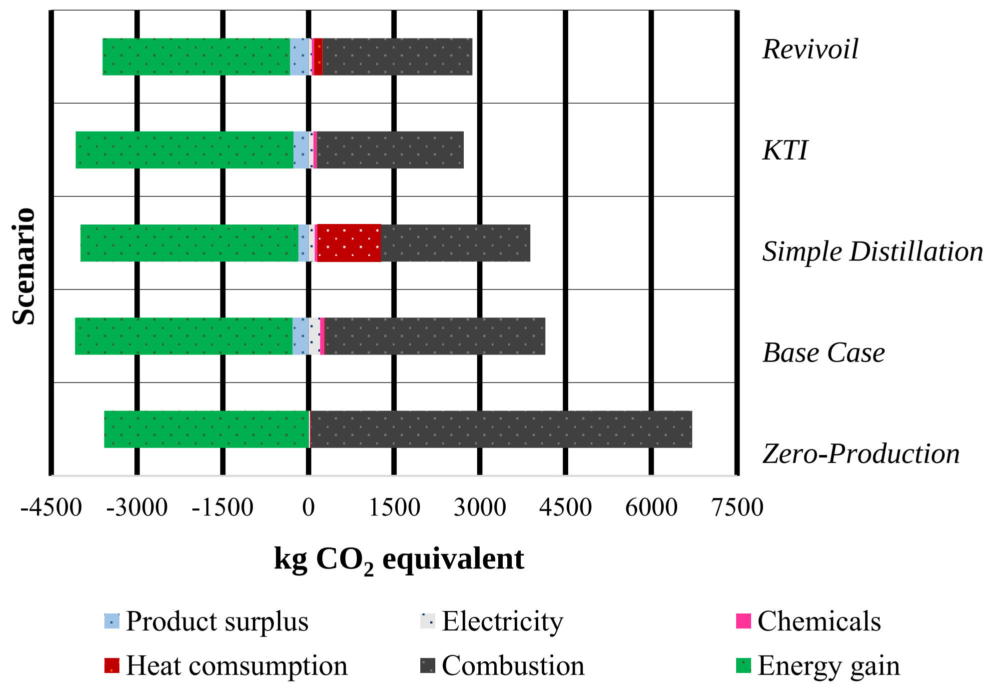
The data inventory of the stages (i.e., raw material acquisition, material processing, product use, and disposal) was combined and then accessed in SimaPro. In addition, the tables C1-C20 in Appendix C show the correspondence between the input inventory from the SimaPro database and input inventory from the secondary data sources (e.g., literature, report and journal).

Figure 4.15 Global warming potential (GWP); (kg CO_2 eq) of each scenario.



Global warming potential (GWP) with the functional unit of a ton of market demand as in Figure 4.15 shows that the zero-production scenario caused the most impact value (3,143 kg CO_2 equivalent), followed by the base case scenario or current practice (59 kg CO_2 equivalent). It can be seen that the zero-production and the base case scenario had a net disadvantage for the environment due to the net positive value of GWP. Whereas the re-refining scenarios (i.e., KTI and Revivoil) and the simple distillation had a net benefit for the environment due to the net negative value of GWP. From the result, KTI scenario had the least impact value (-1,356 kg CO_2 equivalent) that approximately 23 times less than that of the base case scenario. The result showed that the waste treatment method with re-refining process appeared to be a significant decrease in the global warming impact.

Figure 4.16 Contributions of inputs to global warming potential (GWP).



With the functional unit of a ton of petroleum product's market demand in Thailand, the contribution of inputs to GWP is shown in Figure 4.16. For contribution analysis, inventory inputs were grouped into the main inputs (i.e., product surplus, electricity, chemicals, heat consumption for production, combustion fuels and energy gain by combustion of fuels). Overall, the product use stage (i.e., combustion and energy gain) was the largest contributor to the GWP of the used oil management for all scenarios. The combustion caused significantly increase in GWP due to the carbon emission during combustion, whereas the energy gain caused significantly decrease in GWP. Therefore, the product use stage was significantly concerned to improve the waste management system. Focusing on the energy gain, Revivoil scenario led to the small decrease of GWP compared to another re-refining scenario (KTI) because the main products of Revivoil process (i.e., base oil and asphalt) were assumed to be consumed for non-combustion use. The energy gain from the combustion of fuels led to a negative value of GWP, meaning that the energy gain reduces the GWP by compensating energy consumption.

Focusing on the combustion, the contaminant content of products from the base case and the zero-production was not reduced to the desired level, which results in a higher contribution of the combustion to GWP. Whereas, the other alternatives (i.e., the simple distillation, KTI and Revivoil) were generated products at the desired level, resulting in a lower contribution to the combustion and thus to net GWP.

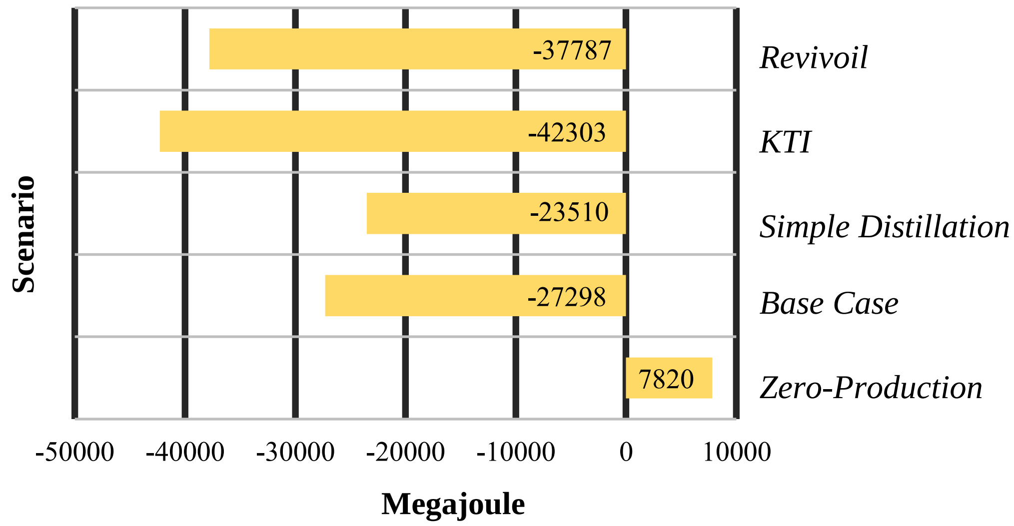
However, the simple distillation process significantly required more heat than the re-refining processes (i.e., KTI and Revivoil), resulting in a higher contribution to GWP. Due to less heat required, the re-refining scenario (KTI and Revivoil) was more suitable practice in comparison with other alternatives in terms of GWP.

Table 4.30 Global warming potential (GWP) of product surplus

Scenario	**Product surplus (unit: kg)**			**Global warming potential (GWP) (unit: kg CO_2 eq)**
	Bitumen	**Base oil**	**Fuel oil**	
Revivoil	103	541	0	-324
KTI	0	494	0	-263
Simple distillation	514	0	0	-178
Base case	0	0	647	-276
Zero-production	0	0	0	0

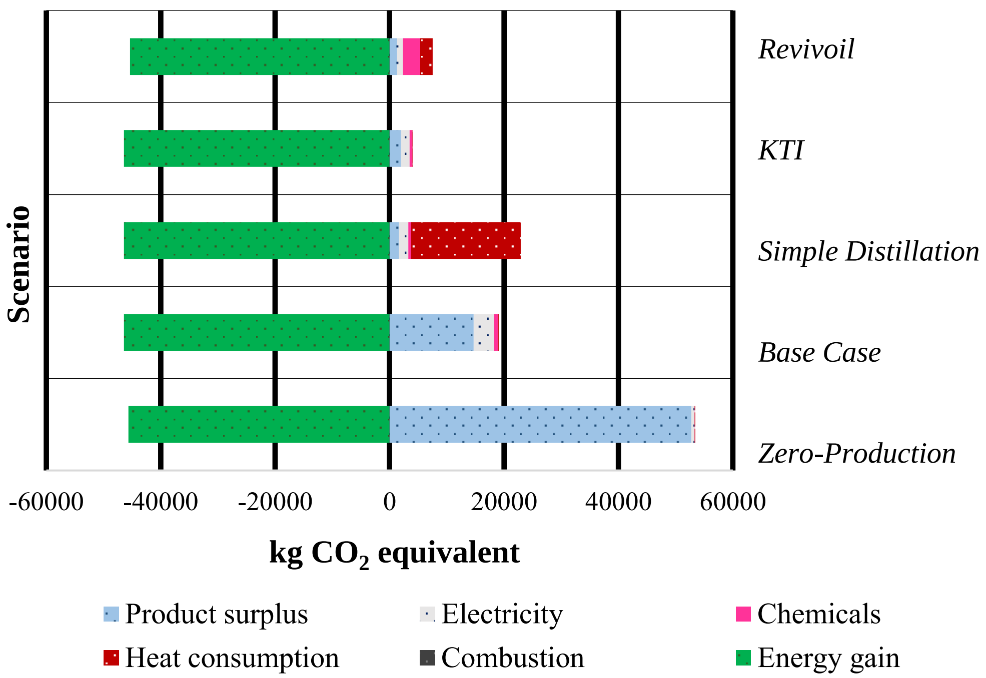
From Table 4.30, the product surplus generated by Revivoil process was the most avoided GWP, followed by the base case and KTI. Even though the simple distillation process produced a greater amount of product surplus than KTI process, KTI process reduced more GWP than the simple distillation process. It can be seen that the type of product surplus influenced on the decreasing of GWP, and the base oil was the most influential product surplus for GWP reduction.

Figure 4.17 Depletion of Fossil Fuels (MJ) of each scenario.



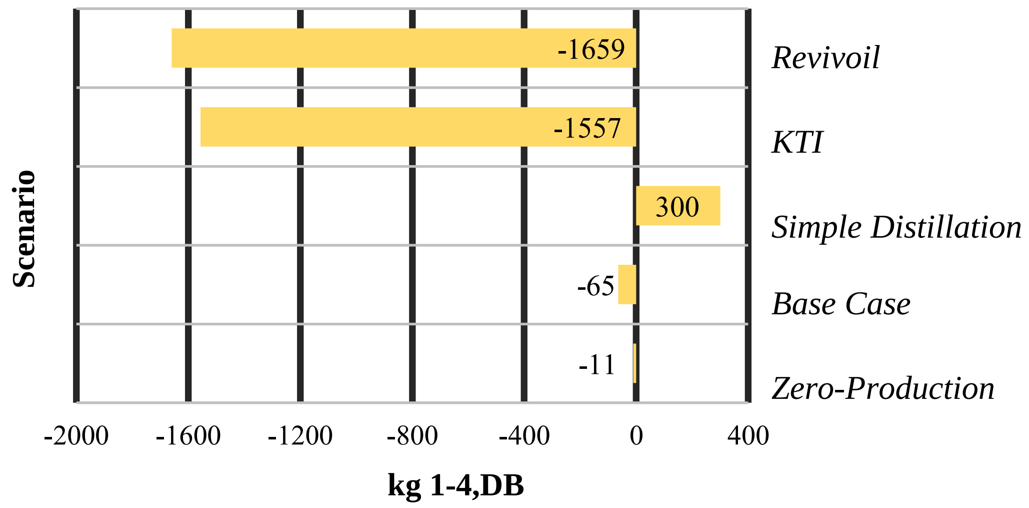
With the functional unit of a ton of petroleum product's market demand in Thailand, Figure 4.17 shows that all scenarios had the negative impact value of the depletion of fossil fuels except the zero-production scenario that showed the net positive value (7,820 MJ). From the result, KTI scenario had the least impact value of the depletion of fossil fuels (-42,303 MJ), followed by Revivoil scenario (-37,787 MJ). Therefore, the re-refining scenarios (KTI and Revivoil) were the most suitable practices in comparison with other alternatives to make a net benefit for the environment, whereas the base case or current practice had the lower impact value than the simple distillation. It can be seen that the simple distillation was inappropriate in terms of energy efficiency.

Figure 4.18 Contributions of inputs to the depletion of fossil fuels.



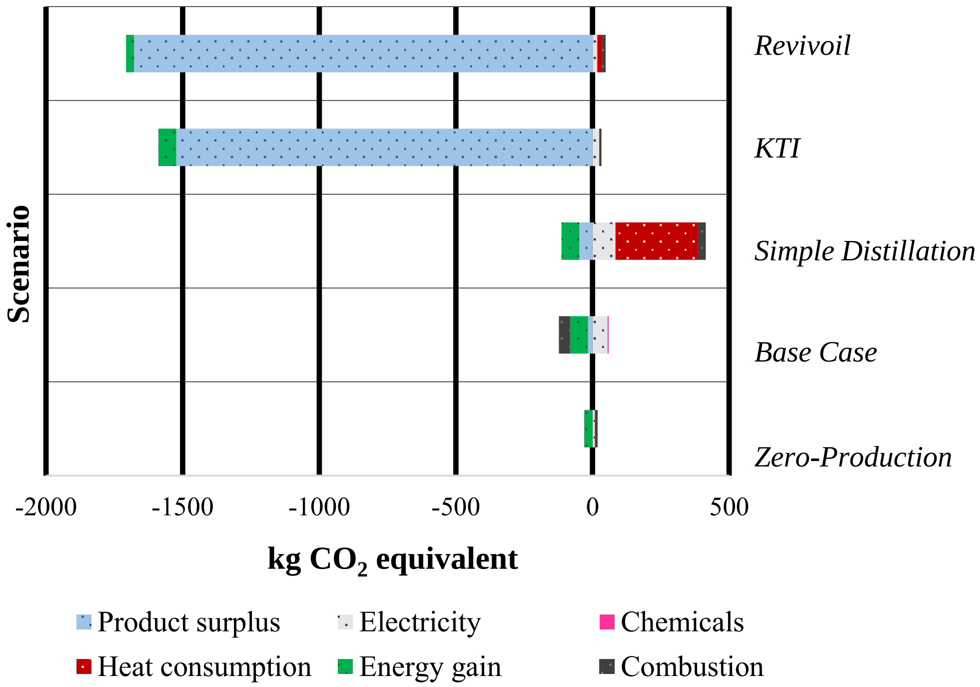
According to Figure 4.18, the energy gain from burning fossil fuels was mainly contributed to the reduction in depletion of fossil fuels for all scenario. In addition, the re-refining (KTI and Revivoil) and the simple distillation obviously reduced the fossil fuel depletion from the product surplus compared to the others, which led to the reduction of the net impact value. However, the simple distillation required more heat than the re-refining processes, resulting in a large contribution of heat consumption to the fossil fuel depletion. Whereas, the combustion of petroleum products had no effect on the depletion of fossil fuels.

Figure 4.19 Human toxicity (kg 1,4-DB) of each scenario.



With the functional unit of a ton of petroleum product's market demand in Thailand, Figure 4.19 shows that the simple distillation scenario obviously had the largest impact value of human toxicity (300 kg 1,4-DB equivalent), whereas the other scenarios had the negative value of human toxicity, meaning the other scenarios caused the net benefit for environment. For the human toxicity, Revivoil scenario had the least impact value (-1,659 kg 1,4-DB equivalent), followed by KTI scenario (-1,557 kg 1,4-DB equivalent). Due to the large amount production of base oil, the scenarios (KTI and Revivoil) had the obvious negative impact value. It can be seen that the re-refining scenarios were the most suitable practice in terms of human toxicity.

Figure 4.20 Contributions of inputs to human toxicity.



According to Figure 4.20, the product surplus was the largest contributor to avoid the human toxicity for the re-refining scenarios (KTI and Revivoil) due to the large amount production of the base oil, whereas the others (i.e., electricity, chemicals and the product use stage) had minor effects on the human toxicity. However, the simple distillation required more heat consumption than the re-refining processes, resulting in significant contribution to human toxicity.

CHAPTER V
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

From this study, the used lubricating oil obtained from the auto service located in Bangkok was about 16,357 ton/year. It needs to be managed properly through the entire of the methods of formal management. The goals of this study were to calculate the amount of the secondary products generated by the formal management and evaluate the environmental impacts of the scenarios of the used lubricating oil treatment, using material flow analysis (MFA) and life cycle assessment (LCA). For MFA, the formal management of the used lubricating oil in Thailand was separated into 5 options, i.e., recovery (WTC 041), fuel blending (WTC 042), distillation (WTC 049), re-refining (WTC 049) and hazardous waste incineration (WTC 075). The allocation of the used lubricating oil mainly distributed to fuel blending (WTC 042), followed by distillation (WTC 049). For LCA, the used lubricating oil management was separated into 5 scenarios, i.e., the base case or current practice, the zero-production, the simple distillation, the re-refining processes (KTI and Revivoil). Each scenario included 4 stages, i.e., raw material acquisition, material processing, product use, and disposal. All scenarios were evaluated to find the appropriate treatment for minimizing environmental impacts.

The results from MFA using STAN software show that the secondary products (i.e., diesel, asphalt, light ends, base oil, and fuel oil) from the used lubricating oil were mainly contributed to diesel by 11,074 tons (67.71%), followed by asphalt by 3,318 tons (20.28%). While, in fact, the base oil production was extremely low, the base oil was expected to be the main product due to its high value. As a consequence, to increase the base oil production, the allocation ratio of recycling to re-refinery need to be reduced. Most of the secondary products contained the contaminants in the desired level except the wastewater that is classified as hazardous waste, thus the wastewater must be treated in the wastewater treatment before discharge to water resources.

The results of from LCA using SimaPro software show that the re-refining scenarios (KTI and Revivoil) obviously presented the least impact value in all impact categories, i.e., global warming potential (GWP), the depletion of fossil fuels and human toxicity. Therefore, the re-refining processes (KTI and Revivoil) were the appropriate methods in order to reduce environmental impacts. Regarding the contribution to the impacts, the significant contributor to the LCA result was the use of products (i.e., combustion of fuels and energy gain from the combustion) for global warming potential (GWP). The combustion caused a significant increase in GWP, whereas the energy gained by the combustion caused a significant decrease in GWP. For depletion of fossil fuels, the product surplus and the energy gain from the combustion were the significant contributors. For human toxicity, the surplus of base oil production was the most significant contributor.

In addition, the heat consumption was the huge effect on all impacts (i.e., GWP, depletion of fossil fuels and human toxicity). Comparing the re-refining scenarios (KTI and Revivoil) and the simple distillation, it can be seen that the simple distillation required more energy consumption leading to an increase of impact value. Therefore, the simple distillation was inappropriate in terms of energy efficiency. Whereas, the other inputs (i.e., electricity, chemicals and heat) were the minor contributors to the GWP except for the simple distillation scenario.

5.2 Recommendations

Firstly, MFA and LCA was evaluation tool focusing on environmental issues. In addition, the other evaluation tools (e.g., risk assessment, multiple-criteria decision analysis, and cost-benefit analysis) should be applied with the MFA and LCA to evaluate the different aspects (e.g., legal, sociology, and economics) for conducting the feasibility approach. Although the LCA results showed that the re-refining (KTI and Revivoil) were the most appropriate scenarios in terms of environmental aspects, the re-refining processes were uneconomical due to high investment cost.

Secondly, the used oil collected from the auto services in Bangkok was about 16,000 ton annually. Whereas, KTI and Revivoil process needed the annual minimum capacity of 40,000 ton and 60,000 ton; respectively for profitability (Kupareva *et al.*, 2013). Therefore, the used lubricating oil should be collected in all parts of Thailand to gain the higher capacity of feedstock. The nationwide capacity of used lubricating oil collected from the automotive and industrial sectors was about 150,000 ton annually, which is applicable in KTI and Revivoil process. It can be seen that the net profit depended on the capacity of used lubricating oil as feedstock in the process, which was a limitation in this study.

Thirdly, the composition of used oil had a significant effect on MFA and LCA results because the composition of used oil related to the variables in LCA inventory, e.g., heating value of products, material and utility consumption. In this study, the composition of the used oil is shown in Tables 4.2 – 4.3. Whereas, the composition of the used oil from journal review (Zubaidi *et al.*, 2018) was insignificantly different from the survey. As mentioned, the composition of the used oil was one of relevant variables to evaluate the environmental impacts. Therefore, the uncertain variables (e.g., oil composition, heating value, mass allocation of the output flows, and net market demand) should be tested in the sensitivity analysis to identify the impact of variables on MFA and LCA results.

Finally, the functional unit in LCA should be set as a 1,000 US dollar of net profit of petroleum products instead of a ton of net market demand of petroleum products because net profit was applicable in terms of environmental economics, which was concerned with benefits of environment and long-term feasibility approach. The difference of functional unit significantly affected the LCA results in spite of the same inventory data because the allocation of mass production was different to the allocation of product sales. The LCA result based on net market demand indicated the ratio of environmental impact to product demand (mass basis), whereas LCA result based on net profit indicated the ratio of environmental impact based on the profitability of method after accounting for all costs and taxes (money basis).

For calculation, net profit was equal to the subtraction of net revenue and net expenses. Net revenue was calculated by the multiplication of the net market demand of petroleum products and the sale price of each product (i.e., diesel, base oil, fuel oil, gasoline, LPG and asphalt). Net expenses were calculated by the summation of costs, e.g., financial cost, operating cost, tax and investment cost. It can be seen that the setting of the functional unit would have an effect on LCA results.

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APPENDICES

Appendix A The calculation of the proportion of petroleum product

The proportion of primary and secondary production was directly unavailable to obtain. The secondary production was obtained by calculation based on secondary data sources, e.g., literature review and journal. The proportion of primary production was assumed to obtain by the difference between Thailand's market demand shown in Table 4.12 and the secondary production. The proportion of secondary production had to be calculated based on the functional unit of a ton of market demand of petroleum products and shown in Table 4.11 that indicated the secondary products in each scenario. The results were calculated by the Equation 1. The summation of petroleum products was equal to 1,000 kg based on the functional unit.

Equation 1: The calculation of the proportion of petroleum product

$$\text{The amount of petroleum product (kg)} = \sum_{i=1}^{9} \frac{C_i \, x \, X_i}{10}$$

Where, *i* = type of the used oil components

C = composition percentage of the used oil (%) according to Table 4.2

X = mass allocation percentage (%) according to Tables 4.6-4.10 regarding to scenario related

- The base case scenario was related to Table 4.6
- The simple distillation scenario was related to Table 4.8
- Revivoil scenario was related to Table 4.9
- KTI scenario was related to Table 4.10
- The zero-production scenario was assumed that mass allocation percentage of all components in the used oil was equal to zero.

Note: Explanatory legend is expressed below Equation 1

- Petroleum products refer to light ends, diesel, wastewater, fuel oil, bitumen (asphalt) and base oil.
- In each scenario, the petroleum products are not necessary to be 1,000 kg of products due to the non-ideal reactors and the leakage during transportation.

Example

From the base case scenario, fuel oil was the focused petroleum product that contained 9 components. In the calculation example, the amount of lube oil content in fuel oil was calculated according to Table 4.2 and Table 4.6. The total amount of fuel oil in the base case scenario was shown below,

The amount of lube oil	= 86.01 x 93.1/10	= 801 kg
The amount of light naphtha	= 5.30 x 95/10	= 50 kg
The amount of gasoline	= 0.07 x 95/10	= 1 kg
The amount of diesel	= 1.32 x 95/10	= 13 kg
The amount of contaminated water	= 0.27 x 1/10	= 0 kg
The amount of sulfur	= 0.74 x 50/10	= 4 kg
The amount of heavy metals	= 0.01 x 50/10	= 0 kg
The amount of suspended solid	= 5.31 x 50/10	= 27 kg
The amount of ash	= 0.98 x 50/10	= 5 kg

The total amount of fuel oil in the base case scenario

= 801+50+1+13+4+27+5 kg

= 899 kg

The amount of fuel oil in the base case scenario is equal to 899.46 kilograms that indicates in Table 4.13, and the other products in all the five scenarios have to be continually calculated in the same method.

Appendix B The calculation of the input inventory of the raw material acquisition

For calculation example, the calculation was derived from the primary production in base case scenario. The primary production required crude oil as raw material along with utilities. The primary products consisted of gasoline, diesel, base oil and bitumen, whereas LPG as the imported product and fuel oil as the surplus product was excluded from this calculation. Equation B was derived to convert primary production to the amount of displaced products. The result of calculation shown in Table B1 was the input inventory, i.e., crude oil, electricity, natural gas and water.

Equation B: The input inventory of the raw material acquisition

$$\text{The input inventory (kg)} = \sum_{i=1}^{4} P_j x\, k_{ij}$$

Where,	i	=	type of the displaced product
	j	=	type of the primary product except the surplus product and LPG
	P	=	Primary production (kg)
	k	=	The inventory parameters of displaced product according to Table 4.18 (unit of displaced product / kg)

<u>Example</u>

The primary products in the base case scenario was gasoline, diesel, base oil and bitumen, whereas LPG and fuel oil were excluded from this calculation.

1st primary product (gasoline)

According to Table 4.13, the production of gasoline is equal to 211 kg

Crude oil	= 211 kg gasoline x (1.11 kg /kg gasoline)	=	235 kg
Electricity	= 211 kg gasoline x (1.33×10^{-1} MJ/ kg gasoline)	=	28 MJ
Natural gas	= 211 kg gasoline x (5.61×10^{-2} kg/ kg gasoline)	=	12 kg
Water	= 211 kg gasoline x (3.88×10^{-1} kg/ kg gasoline)	=	82 kg

2nd primary product (diesel)

According to Table 4.13, the production of diesel is equal to 491 kg

Crude oil	= 491 kg diesel x (1.11 kg /kg diesel)	=	545 kg
Electricity	= 491 kg diesel x (1.44×10^{-1} MJ/ kg diesel)	=	71 MJ
Natural gas	= 491 kg diesel x (4.77×10^{-2} kg/ kg diesel)	=	23 kg
Water	= 491 kg diesel x (3.32×10^{-1} kg/ kg diesel)	=	163 kg

3rd primary product (base oil)

According to Table 4.13, the production of base oil is equal to 176 kg

Crude oil	= 176 kg diesel x (1.08 kg /kg diesel)	=	190 kg
Electricity	= 176 kg diesel x (2.86×10^{-1} MJ/ kg diesel)	=	50 MJ
Natural gas	= 176 kg diesel x (1.13×10^{-1} kg/ kg diesel)	=	20 kg
Water	= 176 kg diesel x (3.88×10^{-1} kg/ kg diesel)	=	57 kg

4th primary product (bitumen)

According to Table 4.13, the production of bitumen is equal to 3 kg

Crude oil	= 3 kg diesel x (1.01 kg /kg diesel)	=	3 kg
Electricity	= 3 kg diesel x (5.27×10^{-2} MJ/ kg diesel)	=	0 MJ
Natural gas	= 3 kg diesel x (8.25×10^{-3} kg/ kg diesel)	=	0 kg
Water	= 3 kg diesel x (3.03×10^{-1} kg/ kg diesel)	=	1 kg

Total amount of displaced products in the base case scenario was shown in Table 4.19 and calculated as shown below. The other scenarios have to be continually calculated in the same method.

Crude oil	=	235 + 545 + 190 + 3	=	973 kg
Electricity	=	28 + 71 + 50 + 0	=	149 MJ
Natural gas	=	12 + 23 + 20 + 0	=	55 kg
Water	=	82 + 163 + 57 + 1	=	303 kg

Appendix C The LCA inventory of corresponding input from SimaPro software

The inventory of all scenarios from SimaPro software are shown in Tables C1-C19, which included 4 stages (i.e., raw material acquisition, material processing, product use and disposal) except material processing for zero-production scenario.
The positive value means the inputs cause the increase impacts, whereas the negative value means the inputs cause the reduced impacts.

Moreover, the sensitivity analysis of this study was indirectly evaluated by scoring the inventory data to identify a creditability of data assessment, which led to the uncertainty results.

Table C1 Description of data credibility

Data credibility	Description
1	The inventory data directly related to primary data (e.g., survey, interview and experiment) or secondary data (e.g., academic journal and literature review), which was available in SimaPro database
0.9	The inventory data directly related to secondary data (e.g., government sources and non-scholarly sources), which was available in SimaPro database
0.8	The inventory data was the corresponding entry related to primary data (e.g., survey, interview and experiment) or secondary data (e.g., academic journal and literature review) that was unavailable in SimaPro database.
0.7	The inventory data was the corresponding entry related to secondary data (e.g., government sources and non-scholarly sources) that was unavailable in SimaPro database

Table C2 The SimaPro inventory of base case scenario in raw material acquisition stage

Base Case Scenario (Stage 1: Raw Material Acquisition)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Heavy fuel oil at refinery (1.0wt.% S), from crude oil, fuel supply, production mix, at refinery, 1 wt.% sulphur EU-27 S	Fuel oil	646.66	kg	0.9
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Oil, crude	Crude oil	882.21	kg	0.9
Water, process, unspecified natural origin/kg	Water	271.13	kg	1
Gas, natural/kg	LPG	11.53	kg	1
Gas, natural, feedstock, 46.8 MJ per kg	Natural Gas	50.59	kg	1
Electricity, natural gas, at power plant/US	Electricity	138.42	MJ	1

Table C3 The SimaPro inventory of base case scenario in material processing stage

Base Case Scenario (Stage 2: Material Processing)				
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sulfuric acid (98% H2SO4), at plant/RER Mass	Sulfuric Acid	9.00	kg	1
Bleaching earth, at plant/RER Mass	Fuller's Earth	18.00	kg	0.8
Heat, district or industrial, natural gas (GLO)| market group for | Alloc Rec, U	Heat	54.05	MJ	1
Electricity, natural gas, at power plant/US	Electricity	838.35	MJ	1
Hydrogen (reformer) E	Hydrogen	5.69	kg	1
Electricity, natural gas, at power plant/US	Electricity	19.80	MJ	1
Heat, district or industrial, natural gas (GLO)| market group for | Alloc Rec, U	Heat	117.11	MJ	1

Table C4 The SimaPro inventory of base case scenario in product use stage

Base Case Scenario (Stage 3: Product Use)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Process steam from light fuel oil, heat plant, consumption mix, at plant, MJ, CH S	Heat of combustion	34,864.80	MJ	0.9
Emissions to Air	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Methane	CH_4	0.18	kg	0.9
Carbon dioxide, fossil	CO_2	3,882.67	kg	0.9
Dinitrogen monoxide	N_2O	-0.11	kg	0.9
Carbon monoxide, fossil	CO	-1.18	kg	0.9
Particulates, unspecified	PM_{Total}	0.77	kg	0.9
Nitrogen oxides	NO_x	-33.79	kg	0.9
Sulfur oxides	SO_x	-38.27	kg	0.9
NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC	0.04	kg	0.9
PAH, polycyclic aromatic hydrocarbons	PAH	-0.02	kg	0.9

Table C5 The SimaPro inventory of base case scenario in disposal stage

Base Case Scenario (Stage 4: Disposal)				
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Limestone	Hydrate Lime	0.11	kg	0.7
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Electricity, natural gas, at power plant/US	Electricity	0.29	MJ	0.9
Phosphoric acid, merchant grade (75% H3PO4) (NPK 0-54-0), at plant/RER Mass	Phosphoric Acid	0.00	kg	0.9
Iron(II) chloride (GLO)| production | Alloc Rec, U	Iron Chloride	0.06	kg	0.7
Process steam from heavy fuel oil, heat plant, consumption mix, at plant, MJ CH S	Steam	10.27	MJ	0.9
Emissions to Water	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sulfur	Sulfur	7.40	kg	0.9
Heavy metals to water (unspecified)	Heavy Metals	0.06	kg	0.9
Suspended solids, unspecified	Unknown Solid + Ash	62.90	kg	0.9

Table C6 The SimaPro inventory of zero-production scenario in raw material acquisition stage

Zero-Production Scenario (Stage 1: Raw Material Acquisition)				
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Oil, crude	Crude oil	1,077.62	kg	0.9
Water, process, unspecified natural origin/kg	Water	334.28	kg	1
Gas, natural/kg	LPG	11.53	kg	1
Gas, natural, feedstock, 46.8 MJ per kg	Natural Gas	60.60	kg	1
Electricity, natural gas, at power plant/US	Electricity	163.40	MJ	1

Table C7 The SimaPro inventory of zero-production scenario in product use stage

Zero-Production Scenario (Stage 3: Product Use)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Process steam from light fuel oil, heat plant, consumption mix, at plant, MJ, CH S	Heat of combustion	34,864.80	MJ	0.9
Emissions to Air	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Methane	CH_4	0.10	kg	0.9
Carbon dioxide, fossil	CO_2	6,656.00	kg	0.9
Dinitrogen monoxide	N_2O	0.04	kg	0.9
Carbon monoxide, fossil	CO	0.59	kg	0.9
Particulates, unspecified	PM_{Total}	0.21	kg	0.9
Nitrogen oxides	NO_x	7.61	kg	0.9
Sulfur oxides	SO_x	9.16	kg	0.9
NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC	0.06	kg	0.9
PAH, polycyclic aromatic hydrocarbons	PAH	0.00	kg	0.9

Table C8 The SimaPro inventory of zero-production scenario in disposal stage

Zero-Production Scenario (Stage 4: Disposal)				
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Limestone	Hydrate Lime	1.14	kg	0.7
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Electricity, natural gas, at power plant/US	Electricity	2.86	MJ	0.9
Phosphoric acid, merchant grade (75% H3PO4) (NPK 0-54-0), at plant/RER Mass	Phosphoric Acid	0.00	kg	0.9
Iron(II) chloride (GLO)| production | Alloc Rec, U	Iron Chloride	0.57	kg	0.7
Process steam from heavy fuel oil, heat plant, consumption mix, at plant, MJ CH S	Steam	102.13	MJ	0.9
Emissions to Water	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sulfur	Sulfur	7.40	kg	0.9
Heavy metals to water (unspecified)	Heavy Metals	0.06	kg	0.9
Suspended solids, unspecified	Unknown Solid + Ash	62.90	kg	0.9

Table C9 The SimaPro inventory of simple distillation scenario in raw material acquisition stage

Simple Distillation Scenario (Stage 1: Raw Material Acquisition)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Pitch (GLO)| market for pitch | Alloc Rec, U	Bitumen	513.96	kg	0.9
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Oil, crude	Crude oil	541.48	kg	0.9
Water, process, unspecified natural origin/kg	Water	168.98	kg	0.9
Gas, natural/kg	LPG	11.53	kg	0.9
Gas, natural, feedstock, 46.8 MJ per kg	Natural Gas	36.92	kg	0.9
Electricity, natural gas, at power plant/US	Electricity	95.05	MJ	0.9

Table C10 The SimaPro inventory of simple distillation scenario in material processing stage

Simple Distillation Scenario (Stage 2: Material Processing)				
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sodium chloride, at plant/RNA	Sodium Chloride	3.10	kg	1
Electricity, natural gas, at power plant/US	Natural Gas	5,440.00	MJ	1
Electricity, residual fuel oil, at power plant/US	Electricity from Fuel Oil	89.50	kWh	1
Hydrogen (reformer) E	Hydrogen	6.15	kg	1
Electricity, natural gas, at power plant/US	Electricity	21.40	MJ	1
Heat, district or industrial, natural gas (GLO)| market group for | Alloc Rec, U	Heat	126.60	MJ	1

Table C11 The SimaPro inventory of simple distillation scenario in product use stage

Simple Distillation Scenario (Stage 3: Product Use)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Process steam from light fuel oil, heat plant, consumption mix, at plant, MJ, CH S	Heat of combustion	34,864.8	MJ	0.9
Emissions to Air	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Methane	CH_4	0.05	kg	0.9
Carbon dioxide, fossil	CO_2	2,583.52	kg	0.9
Dinitrogen monoxide	N_2O	0.12	kg	0.9
Carbon monoxide, fossil	CO	1.71	kg	0.9
Particulates, unspecified	PM_{Total}	1.28	kg	0.9
Nitrogen oxides	NO_x	22.67	kg	0.9
Sulfur oxides	SO_x	9.36	kg	0.9
NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC	0.66	kg	0.9
PAH, polycyclic aromatic hydrocarbons	PAH	0.02	kg	0.9

Table C12 The SimaPro inventory of simple distillation scenario in disposal stage

Simple Distillation Scenario (Stage 4: Disposal)				
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Limestone	Hydrate Lime	< 0.01	kg	0.7
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Electricity, natural gas, at power plant/US	Electricity	0.01	MJ	0.9
Phosphoric acid, merchant grade (75% H3PO4) (NPK 0-54-0), at plant/RER Mass	Phosphoric Acid	< 0.01	kg	0.9
Iron(II) chloride (GLO)| production | Alloc Rec, U	Iron Chloride	< 0.01	kg	0.7
Process steam from heavy fuel oil, heat plant, consumption mix, at plant, MJ CH S	Steam	0.28	MJ	0.9
Emissions to Water	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sulfur	Sulfur	0.07	kg	0.9
Heavy metals to water (unspecified)	Heavy Metals	0.02	kg	0.9
Suspended solids, unspecified	Unknown Solid + Ash	0.63	kg	0.9

Table C13 The SimaPro inventory of KTI scenario in raw material acquisition stage

KTI Scenario (Stage 1: Raw Material Acquisition)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Petroleum refining coproduct, unspecified, at refinery/kg/US	Base oil	494.06	kg	0.7
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Oil, crude	Crude oil	581.96	kg	1
Water, process, unspecified natural origin/kg	Water	181.05	kg	1
Gas, natural/kg	LPG	11.53	kg	1
Gas, natural, feedstock, 46.8 MJ per kg	Natural Gas	25.98	kg	1
Electricity, natural gas, at power plant/US	Electricity	73.91	MJ	1

Table C14 The SimaPro inventory of KTI scenario in material processing stage

KTI Scenario (Stage 2: Material Processing)				
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Additives	Additives	0.21	kg	0.8
Water, cooling, unspecified natural origin, TH	Water	2.00	m^3	1
Electricity, natural gas, at power plant/US	Electricity	94.00	kWh	1
Hydrogen gas, from diaphragm technology, at plant/RER Mass	Hydrogen	2.42	kg	1
Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S	Nitrogen	3.03	kg	1
Steam, in chemical industry (GLO)| market for | Alloc Rec, U	Steam	26.50	kg	1
Hydrogen (reformer) E	Hydrogen	6.04	kg	1
Electricity, natural gas, at power plant/US	Electricity	21.03	MJ	1
Heat, district or industrial, natural gas (GLO)| market group for | Alloc Rec, U	Heat	124.38	MJ	1

Table C15 The SimaPro inventory of KTI scenario in product use stage

KTI Scenario (Stage 3: Product Use)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Process steam from light fuel oil, heat plant, consumption mix, at plant, MJ, CH S	Heat of combustion	34,864.8	MJ	0.9
Emissions to Air	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Methane	CH_4	0.10	kg	0.9
Carbon dioxide, fossil	CO_2	2,553.60	kg	0.9
Dinitrogen monoxide	N_2O	0.04	kg	0.9
Carbon monoxide, fossil	CO	0.63	kg	0.9
Particulates, unspecified	PM_{Total}	0.55	kg	0.9
Nitrogen oxides	NO_x	5.69	kg	0.9
Sulfur oxides	SO_x	2.71	kg	0.9
NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC	0.21	kg	0.9
PAH, polycyclic aromatic hydrocarbons	PAH	0.00	kg	0.9

Table C16 The SimaPro inventory of KTI scenario in disposal stage

KTI Scenario (Stage 4: Disposal)				
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Limestone	Hydrate Lime	0.05	kg	0.7
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Electricity, natural gas, at power plant/US	Electricity	0.12	MJ	0.9
Phosphoric acid, merchant grade (75% H3PO4) (NPK 0-54-0), at plant/RER Mass	Phosphoric Acid	< 0.01	kg	0.9
Iron(II) chloride (GLO)| production | Alloc Rec, U	Iron Chloride	0.02	kg	0.7
Process steam from heavy fuel oil, heat plant, consumption mix, at plant, MJ CH S	Steam	4.35	MJ	0.9
Emissions to Water	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sulfur	Sulfur	0.13	kg	0.9
Heavy metals to water (unspecified)	Heavy Metals	0.06	kg	0.9
Suspended solids, unspecified	Unknown Solid + Ash	53.10	kg	0.9

Table C17 The SimaPro inventory of Revivoil scenario in raw material acquisition stage

Revivoil Scenario (Stage 1: Raw Material Acquisition)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Pitch (GLO)| market for pitch | Alloc Rec, U	Bitumen	102.97	kg	0.9
Petroleum refining coproduct, unspecified, at refinery/kg/US	Base oil	541.24	kg	0.7
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Oil, crude	Crude oil	726.19	kg	1
Water, process, unspecified natural origin/kg	Water	224.80	kg	1
Gas, natural/kg	LPG	11.53	kg	1
Gas, natural, feedstock, 46.8 MJ per kg	Natural Gas	33.25	kg	1
Electricity, natural gas, at power plant/US	Electricity	93.27	MJ	1

Table C18 The SimaPro inventory of Revivoil scenario in material processing stage

Revivoil Scenario (Stage 2: Material Processing)				
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Additives	Additives	10.00	kg	0.8
Water, cooling, unspecified natural origin, TH	Water	0.23	m^3	1
Zeolite	Catalyst	0.25	kg	0.7
Electricity, natural gas, at power plant/US	Electricity	55.00	kWh	1
Hydrogen gas, from diaphragm technology, at plant/RER Mass	Hydrogen	2.50	kg	1
Heavy fuel oil, from crude oil, consumption mix, at refinery EU-15 S	Fuel oil	65.00	kg	1
Steam, in chemical industry (GLO)| market for | Alloc Rec, U	Steam	800.00	kg	1
Hydrogen (reformer) E	Hydrogen	1.65	kg	1
Electricity, natural gas, at power plant/US	Electricity	5.76	MJ	1
Heat, district or industrial, natural gas (GLO)| market group for | Alloc Rec, U	Heat	34.05	MJ	1

Table C19 The SimaPro inventory of Revivoil scenario in product use stage

Revivoil Scenario (Stage 3: Product Use)				
Avoided products	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Process steam from light fuel oil, heat plant, consumption mix, at plant, MJ, CH S	Heat of combustion	34,864.8	MJ	0.9
Emissions to Air	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Methane	CH_4	0.09	kg	0.9
Carbon dioxide, fossil	CO_2	2,583.52	kg	0.9
Dinitrogen monoxide	N_2O	0.06	kg	0.9
Carbon monoxide, fossil	CO	0.77	kg	0.9
Particulates, unspecified	PM_{Total}	0.39	kg	0.9
Nitrogen oxides	NO_x	10.11	kg	0.9
Sulfur oxides	SO_x	9.19	kg	0.9
NMVOC, non-methane volatile organic compounds, unspecified origin	NMVOC	0.16	kg	0.9
PAH, polycyclic aromatic hydrocarbons	PAH	0.01	kg	0.9

Table C20 The SimaPro inventory of Revivoil scenario in disposal stage

Revivoil Scenario (Stage 4: Disposal)				
Resources	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Limestone	Hydrate Lime	0.04	kg	0.7
Materials/fuels	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Electricity, natural gas, at power plant/US	Electricity	0.10	MJ	0.9
Phosphoric acid, merchant grade (75% H3PO4) (NPK 0-54-0), at plant/RER Mass	Phosphoric Acid	< 0.00	kg	0.9
Iron(II) chloride (GLO)| production | Alloc Rec, U	Iron Chloride	0.02	kg	0.7
Process steam from heavy fuel oil, heat plant, consumption mix, at plant, MJ CH S	Steam	3.49	MJ	0.9
Emissions to Water	**Corresponding Input**	**Amount**	**Unit**	**Data Score**
Sulfur	Sulfur	0.04	kg	0.9
Heavy metals to water (unspecified)	Heavy Metals	< 0.00	kg	0.9
Suspended solids, unspecified	Unknown Solid + Ash	1.42	kg	0.9

Appendix D The environmental impact results of the used lubricating oil management from SimaPro software

The results are shown in Tables D1-D10 which compose of 5 scenarios, i.e., the base case, the zero-production, the simple distillation, KTI and Revivoil. A set of Tables D shows the result of impact categories i.e., global warming potential, depletion of fossil fuels, human toxicity and acidification. The negative value indicates a net benefit for the environment, whereas the positive value indicates a net disadvantage for the environment.

Table D1 Global warming potential (GWP) result from SimaPro software

Contributor	Unit	Scenario				
		Base case	**Zero-production**	**Simple distillation**	**KTI**	**Revivoil**
Product surplus	kg CO_2 eq	-276	0	-178	-263	-324
Electricity	kg CO_2 eq	202	33	108	88	60
Chemicals	kg CO_2 eq	76	1	51	52	39
Heat consumption	kg CO_2 eq	7	11	1,109	10	152
Combustion	kg CO_2 eq	3,859	6,669	2,617	2,567	2,602
Energy gain	kg CO_2 eq	-3,810	-3,572	-3,810	-3,810	-3,277
Total	kg CO_2 eq	59	3,143	-104	-1,356	-733

Table D2 Depletion of fossil fuels result from SimaPro software

Contributor	**Unit**	**Scenario**				
		Base case	**Zero-production**	**Simple distillation**	**KTI**	**Revivoil**
Product surplus	MJ	14,713	52,743	1,678	1,970	1,301
Electricity	MJ	3,498	575	1,601	1,521	1,043
Chemicals	MJ	812	10	480	491	3,009
Heat consumption	MJ	117	136	19,168	153	2,206
Combustion	MJ	0	0	0	0	0
Energy gain	MJ	-46,438	-45,645	-46,438	-46,438	-45,344
Total	MJ	-27,298	7,820	-23,510	-42,303	-37,787

Table D3 Human toxicity result from SimaPro software

Contributor	Unit	Scenario				
		Base case	**Zero-production**	**Simple distillation**	**KTI**	**Revivoil**
Product surplus	kg 1,4-DB	0	-16	-48	-1,523	-1,678
Electricity	kg 1,4-DB	9	55	84	24	16
Chemicals	kg 1,4-DB	0	2	0	0	2
Heat consumption	kg 1,4-DB	0	1	302	1	17
Combustion	kg 1,4-DB	9	-41	27	7	12
Energy gain	kg 1,4-DB	-30	-66	-66	-66	-29
Total	kg 1,4-DB	-11	-65	300	-1,557	-1,659

CURRICULUM VITAE

Name: Mr. Komsan Toeipomthong

Date of Birth: December 2, 1994

Nationality: Thai

University Education:

2017–2013 Bachelor Degree of Chemical Technology, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

Work Experience:

2016 Position: Trainee in Process division

Company name: Bangchak Corporation Public Company Limited