MATERIAL FLOW ANALYSIS (MFA) STUDY FOR SUSTAINABLE MANAGEMENT OF PVC WASTES IN THAIL AND (PHASE III)

Wikanda Khomchu

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Masters of Science
The Petroleum and Petrochemical College, Chulalongkorn University
in Academic Partnership with
The University of Michigan, The University of Oklahoma,
Case Western Reserve University, and Institut Français du Pétrole
2017

ABSTRACT

5873023063: Petroleum Technology Program

Wikanda Khomchu: Material Flow Analysis (MFA) Study for Sustainable Management of PVC Wastes in Thailand (Phase III)

Thesis Advisors: Asst. Prof. Pomthong Malakul, Asst. Prof. Manit Nithitanakul and Dr. Ampira Charoensaeng, 81 pp.

Keywords: Material flow analysis (MFA)/ PVC/ Sustainable management

Polyvinyl chloride (PVC) products are used for domestic consumption more than 400,000 tons annually and tend to be increasing in Thailand. After discarded, these products will become wastes which are being accumulated and could cause several environmental problems if they are disposed by inappropriate method. In previous studies, our group investigated the material flow of PVC in Thailand to handle the PVC waste problems. Material Flow Analysis (MFA) model was developed to estimate the quantity and route of PVC wastes in Thailand. Furthermore, the primary data were collected from recycle shops and landfill sites were used to estimate the amount of PVC wastes that are generated and recycled on yearly basis. Phase III study was carried out in order to further proceed the MFA model by using annual domestic production data from 1971 to 2016 as an input in the model along with an average service lifetime of each product, consumer behaviour and economic decisions and off-spec products for accuracy estimation. Moreover, sheet & film product were included in this investigation in order to expand range of PVC products, in which covers about 93% of total PVC products in Thailand. In addition, the existing primary data were revised along with the new data were from other recycle shops and converters to estimate the amount recycled PVC products in 2015 and 2016 together with recycling ratio of each PVC product in Thailand. Finally, potential improvements of PVC waste management and suitable data collection system are proposed in order to promote environmentally friendly schemes for PVC production and utilization.

บทคัดย่อ

วิกานดา ค้ำชู : การวิเคราะห์การไหลของวัสดุเพื่อศึกษาการจัดการอย่างยั่งยืนของขยะพีวีซีในประเทศไทย (Material Flow Analysis (MFA) Study for Sustainable of PVC Wastes in Thailand Phase III) อ.ที่ปรึกษา: ผศ.ดร.ปมทอง มาลากุล ณ อยุธยา, ผศ.ดร.มานิตย์ นิธิธนากุล และ ดร.อัมพิรา เจริญแสง 81 หน้า

ในประเทศไทยนั้นผลิตภัณฑ์จากพลาสติกพีวีซีมีปริมาณมากกว่า 400,000 ตันต่อปีที่ถูกผลิตขึ้นเพื่อตอบสนองความต้องการภายในประเทศ ซึ่งก่อให้เกิดปัญหาภายหลังจากการใช้งานของขยะผลิตภัณฑ์พลาสติกพีวีซีหากไม่ได้รับการจัดการถูกต้อง ทั้งนี้เพื่อที่จะรับมือกับขยะพีวีซีที่เพิ่มขึ้นอย่างต่อเนื่องในประเทศได้อย่างถูกต้องและเหมาะสมในงานวิจัยในยระยะที่ 1 และ 2 ได้พัฒนาแบบจำลองวิเคราะห์การไหลของวัสดุ เพื่อวิเคราะห์การไหลของผลิตภัณฑ์พีวิซีดังกล่าวหลังการใช้งานและประเมินปริมาณขยะผลิตภัณฑ์พลาสติกพีวีซีในประเทศ ในเบื้องต้นข้อมูลปฐมภูมิถูกเก็บจากร้านรีไซเคิลพีวีซีและบ่อฝังกลบเพื่อประมาณปริมาณขยะพีวีซีที่เกิดขึ้นในแต่ละส่วนที่ถูกรีไซเคิลเพื่อที่จะประเมินปริมาณผลิตภัณฑ์พีวิซีหลังการใช้งานในประเทศได้แม่นยำมากยิ่งขึ้นจึงได้มีการศึกษาในระยะที่ 3 โดยการป้อนข้อมูลของการผลิตพีวีซีในประเทศจากปี พ.ศ. 2514 ถึงปี 2559 ในโมเดลร่วมกับการประมวลผลของอายุการใช้งานเฉลี่ยของแต่ละผลิตภัณฑ์ รวมทั้งพิจารณาปัจจัยพฤติกรรมของผู้บริโภคกับเศรษฐกิจร่วมด้วยและผลิตภัณฑ์ต่ำมาตรฐานการผลิต เพื่อการประมวลผลที่แม่นยำมากขึ้น นอกจากนี้ยังได้เพิ่มผลิตภัณฑ์ชีทและฟิล์มเข้ามาในการศึกษา เพื่อให้คลอบคลุมช่วงของผลิตภัณฑ์พีวีซีในประเทศในให้มากขึ้นถึง 93 % ของทั้งหมด และยังได้รับข้อมูลปฐมภูมิที่มากขึ้นจากร้านรีไซเคิลและกลุ่มแปรรูปพลาสติกรีไซเคิล เพื่อประมาณปริมาณขยะพีวีซีที่ถูกรีไซเคิลในปี พ.ศ. 2558 และ 2559 และหาสัดส่วนการรีไซเคิลของแต่ละผลิตภัณฑ์ ทั้งนี้เพื่อนำข้อมูลที่ได้ไปใช้ในการวางแผนจัดการขยะผลิตภัณฑ์พลาสติกพีวีซีในประเทศเพื่อการพัฒนาที่ยั่งยืน

ACKNOWLEGEMENTS

This study would not have been possible without the assistance of the following people.

First, the author wishes to express my profound gratitude and deep regards to my advisors, Asst. Prof. Pomthong Malakul, Asst. Prof. Manit Nithitanakul and Dr.Ampira Charoensaeng my advisors, for providing abundantly helpful and offering invaluable assistance, kindly support and guidance. Deepest gratitude is also due to the members of the supervisory committee, Asst. Prof. Kitipat Siemanond and Assoc. Prof. Thumrongrut Mungcharoen for their knowledge, assistance and suggestion.

The author also gives thanks to Department of Industrial Works for information supports, Mr. Namsak Choonhajutha and Miss Jirawadee Pipattanatornkul for your kind suggestion and support throughout this research work.

In addition, the author would like to thank the Petroleum and Petrochemical College, ASEAN Vinyl Council Association, and the Center of Excellence on Petrochemicals and Material Technology, Chulalongkorn University, Thailand for the research funding and scholarship.

Special thanks also to my PPC friends and PPC research affairs staff for helping in various aspects, giving creative suggestions and encouragement.

Finally, the author wishes to express my love and gratitude to my family for their understanding, encouragement and always give me greatest love. This thesis will not have been successful, if the author is without them.

TABLE OF CONTENTS

CHAPTER **PAGE**

CHAPTER **PAGE**

LIST OF TABLES

TABLE **PAGE**

TABLE **PAGE**

LIST OF FIGURES

FIGURE **PAGE**

CHAPTER I
INTRODUCTION

Polyvinyl chloride (PVC) is a common plastic used worldwide due to its inherent properties such as durability, corrosive resistance, low cost, and high performance. These properties make PVC suitable for numerous applications, for instance, pipes, profiles, flooring, cable insulation, roofing, packaging, bottling, and the medical applications. In Thailand, the domestic consumption of PVC product is more than 400,000 tons annually and tends to be increasing. Consequently, the post-consumer phase of PVC generates a lot of wastes which has accumulated and could lend to tremendous environmental and human health problems if not treated properly or mismanaged. For instance, plastic waste disposal by landfill of plastic wastes could lead to problems such as land occupancy and soil pollution, while burning or incineration of PVC wastes, even more, generates toxic substances (e.g., Dioxin) which seriously affect human health. In contrast, a more suitable way to handle PVC post-consumer wastes such as recycling can recover PVC material for secondary production which not only could help reduce the need of new material and energy, but also avoid environmental impacts. To handling PVC waste problems systematically and efficiently, it is important to estimate the amount of PVC wastes generated and determine different pathways that PVC wastes are discharged to the environments. Material Flow Analysis (MFA) is a systematic assessment of flow and stock of materials within a temporal and spatial system. The MFA can be used as a tool to identify and analyze the flow of materials added in and removed out from the system. MFA outcome can be used as an indicator for analyzing the flow throughout the life cycles of target materials and increasing the efficiency of material usage.

In previous studies, the MFA model was developed to estimate the route and quantity of PVC wastes in Thailand, using annual production data from 1971 to 2014 as an input along with average service lifetime seven selected PVC products comprised of pipe & fitting, profile, cable, floor covering, floor tile, hose and shoes. The results obtained from MFA model showed that approximately 120,000 to 140,000 tons of PVC wastes were generated during 2013 to 2014. In addition, the primary data collected from recycle shops and landfill sites were used to estimate the amount of

PVC wastes generated and recycled on a yearly basis. It was found that some products were recycled at high percentages such as pipe, cable, and hose but the other products were recycled relatively low portion. For the waste disposal by incineration, the PVC products were found in relatively small amount by 0.004% at the sampling site. It can be seen that the PVC products at their end of life stage have sent to recycle shops and the reminders have released to landfills. Moreover, the waste management or end-of-life scenarios of PVC products were created and evaluated by using life cycle assessment (LCA). The results showed that the global warming potential and energy resource impacts significantly were reduced to be 22 to 58 % and 25 to 72 %, respectively. From the base case scenario, the recycle process indicated a significant role in reducing potential environmental impacts of PVC wastes.

Therefore, this present study aims to further conduct MFA of PVC products in Thailand by considering consumer behavior and economic decisions and taking off-spec products into account for comprehensive estimation. Sheet & Film product is additionally included in this investigation in order to expand the range of PVC products, consequently, this study, eight-PVC products are selected including pipe & fitting, profile, cable, floor covering, floor tile, hose, shoes, and sheet & film. In addition, the existing primary data are revised along with the new data are gathered from new recycle shops and converters in order to update recycled PVC products in years 2013 and 2014. Finally, potential improvements in PVC waste management and appropriate data collection system schemes are suggested with the purpose of promoting environmentally friendly schemes for PVC production and utilization in a sustainable way.

CHAPTER II
BACKGROUND AND LITERATURE REVIEWS

2.1 Background

2.1.1 Definition and Application of PVC

PVC (Polyvinyl-chloride) is one of thermoplastics. Its starting material is Vinyl chloride monomer which is processed to generate PVC by suspension, emulsion and polymerization. The first step of PVC preparation is the production of Chloride. By the method of electrolysis, salt water is disintegrated by ethylene which is component of natural oil or natural gas via "cracking" process.

Passing step by step, vinyl chloride monomer (VCM) is finally produced. After the polymerization process, these monomers assemble to yield the semi-final product named PVC. The characteristic of PVC is hard but easily broken. Moreover, PVC contains many kinds of additives such as, stabilizer and/or plasticizer which result in the unique properties suitable for each application of this plastic. Consequently, ready-to-use powder (premixes) or PVC granules (compounds) is manufactured and changed to be the final product. To enhance its strength, rigidity and modify its color and transparency, various kinds of material must be added to PVC. PVC is a versatile and interesting polymer. A considerable range of additives can be incorporated to this plastic. Because of its polar property and backbone containing the repeated chlorine atoms, PVC is widely utilized for many applications with the different purposes. PVC is nontoxic odorless white power. With features of flame retardant, chemical corrosion resistance, good mechanical, products transparency, electric insulation, and easy processing, PVC can be used to produce section, PCPO, tubing and pipe-fittings, board, sheet, cable sheath, hard or soft tube, blood transfusion equipment, and membrane. However, this special feature comes with its negative effect on environmental pollution. Primarily pressured by Greenpeace’s campaign, the environmental concern of using PVC is dramatically increasing. The main topic of this debate accentuated on the harmful element; Chlorine in the molecule of PVC. As stated by Greenpeace, they desire the reduction of chemistry composed of chlorine to be in the acceptable range. For instance, the massive damage of ozone layer has been basically initiated by chlorofluorocarbons. Furthermore, the long-term effects of these chemicals on environment have been the major concern in the persistent using of synthetic chemicals including poly-chlorinated biphenyls, dioxins and furans from the industrial processes (Leadbitter, 2002).

2.1.2 Classifications and Functions of PVC

PVC can be classified into soft PVC and hard PVC. Soft PVC is used on floors, ceilings and leather. Since it contains a softener (the differences between soft PVC and hard PVC), soft PVC easily turns crisp and hard to store. Functions of soft PVC would be limited. Being resistible to pulling, bending, pressure, hard PVC can be used in framework materials, pipelines, planks and plastic products. Hard PVC possess great value for development andapplications (www.hhhd.chemchina.com).

Table 2.1 shows the application of soft and hard PVC products. Figure 2.2 and 2.3 shows the example soft and hard of PVC products. Table 2.2 indicates the composition and amount PVC resin in each PVC applications to estimate the stocks of PVC in Sweden.

Table 2.1 Soft and hard PVC products (www.hhhd.chemchina.com)

Soft product	Shoes and shoe bottom material
	Human-made leather
	Membrane
	Cable insulant
	Floor leather, wallpaper, foam material
	Others
Hard product	Piping material
	Pipe fitting
	Profile, door and window
	Hard plate, plates and other profiles
	Others

Figure 2.1 Examples of soft PVC products.

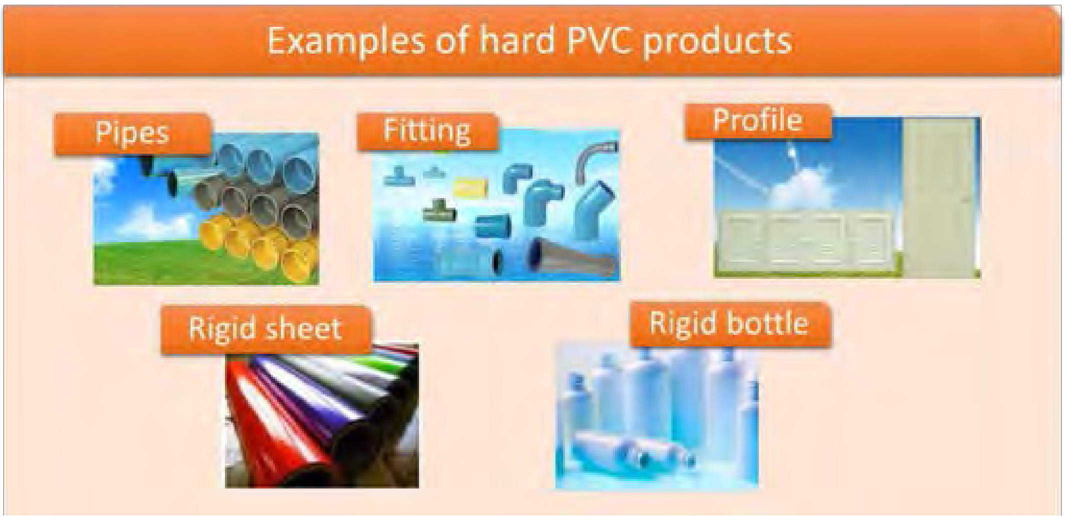

Figure 2.2 Examples of hard PVC products.

Table 2.2 Estimated stocks (in kilotonnes) of PVC and additives in Sweden in 1995 (Kleijn *et al.*,1999)

	PVC(excluding additives)	Phthalates	Lead	Organizing	SnS
Building					
Pipes	919.4	0.0	6.9	0.0	0.0
Flooring	397.7	152.3	0.0	0.1	1.8
Cables	255.0	127.5	7.1	0.0	0.0
Window frames	49.9	0.0	0.2	0.0	0.0
Pipes for electric wire	59.9	0.0	0.3	0.0	0.0
Coated building plate	1.6	0.4	0.0	0.0	0.0
Roof covering	30.0	7.5	0.0	0.0	0.0
Plastisol building app.	45.0	48.0	0.0	0.5	0.0
Other building app.	57.4	0.0	0.3	0.0	0.0
Wall paper	3.0	2.0	0.0	0.0	0.0
Subtotal	1819.0	307.6	14.9	0.6	1.8
Other					
Automotive	0.0	0.0	0.0	0.0	0.0
Electrical equipment	65.6	34.0	0.0	0.0	0.0
Manufacturing	22.3	3.0	0.2	0.0	0.0
Office equipment	23.0	0.0	0.1	0.0	0.0
Other flexible film and foil	15.0	3.8	0.0	0.0	0.0
Packaging	28.2	7.1	0.0	0.0	0.0
Grocery packaging	0.0	0.0	0.0	0.0	0.0
Medical packaging	0.0	0.0	0.0	0.0	0.0
Other rigid film and foil	0.0	0.0	0.0	0.0	0.0
Other plastisol	45.8	0.0	0.0	0.9	0.0
Medical tubes/hoses	10.0	4.0	0.0	0.1	0.0
Other soft tubes/hoses	0.0	0.0	0.0	0.0	0.0
Camouflage fabrics	12.0	6.0	0.3	0.0	0.0
Other artificial leather	15.0	9.8	0.0	0.0	0.0
Subtotal	236.9	67.5	0.7	1.0	0.0
Total	2055.9	375.1	15.6	1.7	1.8

2.2 PVC Industry in Thailand

2.2.1 Thailand PVC Market

PVC demand in 2005 was 1.3 million MT and the prediction of growth from 2005 to 2010 was expected at 7.0 percent. Thailand known as the largest consumer of PVC of South East Asia had PVC supply in 2005 around 1.7 million MT and had an big proportional market 42% of South-East Asia as shown in Figure 2.3. At that moment, TPC group was the largest PVC producer while Singapore, Myanmar, Cambodia, Laos had no PVC plant, so importing from countries around these region was provided (Choonhajutha, 2010).

Figure 2.3 PVC Market Segmentation in South-East Asia (Choonhajutha, 2010).

2.2.2 PVC Resin and Vinyl Chloride Importation and Exportation in Thailand

Thailand PVC resin and Vinyl chloride importation and exportation in 2016 are shown in Table 2.3 (PTIT, 2016).

Table 2.3 PVC and Vinyl chloride importation and exportation in 2016

Products	Import (ton)	Export (ton)
Vinyl chloride	-	81,407
PVC resin	154,322	333,443

2.2.3 PVC Producers in Thailand

Thailand become a net exporter of PVC and will continue in this position over next five years. There are three major PVC resin producers with total capacity of 760,000 MTPA (Table 2.3) and there are many PVC product manufacturers in Thailand as shown in Table 2.4.

Table 2.4 Three major PVC resin producers in Thailand and their capacity (Choonhajutha, 2010)

Company	Capacity (MT) per year
Thai Plastic and Chemaical (TPC)	470,000
Vinylthai (VNT)	190,000
Apex Petrochemical (APC)	100,000

Table 2.5 Examples of PVC products manufacturers in Thailand and their products (Choonhajutha, 2010)

Company	Location	Product
1. Nawaplastic Industries Co., Ltd.	Bangkok	Pipe and fitting
2. Thai Pipe Industry Co., Ltd.	Bangkok	Pipe and fitting
3. Bangkok Paiboon Pipe Co., Ltd.	Bangkok	Pipe and fitting
4. Advanced Pipe Co., Ltd.	Bangkok	Pipe and fitting
5. Untited Enterprise Co., Ltd.	Bangkok	Pipe
6. Thai Vinytech (2002) Co., Ltd.	Bangkok	Pipe
7. S.K.J. Industries Co., Ltd.	Bangkok	Floor covering Table cloth Transparent sheet Artificial leather

Table 2.5 (cont.) Examples of PVC products manufacturers in Thailand and their products (Choonhajutha, 2010)

Company	Location	Product
8. Decorative Plastic Co., Ltd.	Bangkok	Artificial leather Flexible film and sheet Floor covering
9. Siam World Group Co., Ltd.	Bangkok	Pipe and fitting
10. P & ONE Plastic Co., Ltd.	Bangkok	Air condition PVC product

2.2.4 Service Life of PVC in Thailand

Service life of PVC products depends on type of products. In the present day, there are many articles that mention about PVC service life or life expectancy of PVC in wide range, but do not have the exact service life for PVC product. The lifetimes of PVC product in Thailand was estimated by MTEC (2013) and are shown in Table 2.5. Moreover, domestic consumption in Thailand classified by service lifetime which are shot life, medium life, and long life as shown in Figure 2.4.

Table 2.6 Service lifetime of PVC products in Thailand (MTEC, 2013)

PVC Application	Lifetime	
Medical	S	1-2 years
Film	S	
Shoes	S	
Rigid sheet	S	
Soft sheet	M	2-10 years
Floortile	M	
Hose	M	
Pipe	L	>10 years
Wire & Cable	L	
Rigid profile	L	
Soft profile + Sealant +Body Coating	L	

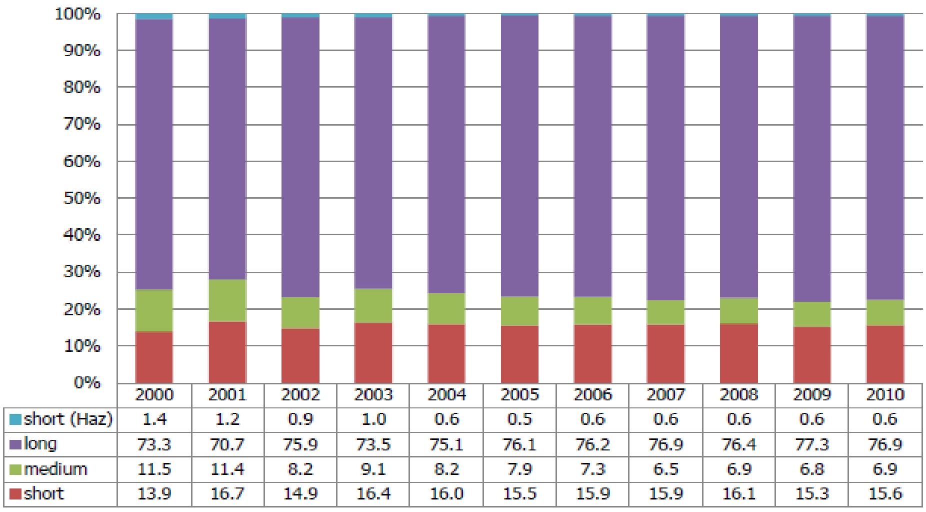

Figure 2.4 Domestic consumption in Thailand classified by service lifetime.

2.3 PVC Waste Management

Recycling consists of collecting, cleaning and separating, processing waste products then, turning them into sellable products. Recycling process may occur during manufacturing process or at the post-consumer stage. For the latter stage, collected plastic waste must be chopped, reenter into the plastic making process, next reproduced to be recycled plastics.

2.3.1 Classifications of PVC Recycling

2.3.1.1 Mechanical Recycling of PVC

Considered as a routinely and simply technical recycling method, the mechanical recycling is the most widely used method in plastic industries. This promising method is efficient whenever the availability of sufficient quantities of homogenous and source separated waste stream exist. Without any alteration in the chemical composition of the plastic raw material, conventional mechanical recycling processes consist of separating, grinding and feeding of ground product into the conversion equipment. After collecting, categorizing by machines and/or by human in reprocessing plants, plastics are cut into tiny pieces (flakes) by a high-speed grinder. After that, they are cleaned with a detergent and water spray. Having been melted down and cast into pellets, the dry flakes are now suitable for processing new plastic products (Mersiowsky, 2001).

2.3.1.2 Chemical Recycling of PVC

Significant limitations of this mechanical recycling method are down-cycling effects and adversity of regaining clean raw materials. Compared to the mechanical recycling, the better method called chemical recycling is continuously gaining the popularity in most of the current research. Especially, laminated films which is very difficult to delaminate because of their inseparable adherence to each layer, this kind of plastics is not capable of being sorted into a single polymer stream. Thus, waste from different sources containing these mixed plastics is a current problem of chemical recycling process. The chemical recycling is less sensitive to unsorted or contaminated waste products. Even though, according to its incomparable energy consumption to the mechanical recycling, the chemical recycling is known as the less worthy method. Depend on the idea of turning plastic waste into the ground chemicals, the feedstock or chemical recycling requires heat, chemical agents and catalysts. Next, Purification and reuse of obtained products in petrochemical industries are applied to produce the same or a related polymer. To manage the chemical recycling of PVC wastes, “thermal cracking” which is conducted by hydrogenation, pyrolysis or gasification is one generally known approach. Given by this approach, a polyene material is the main intermediate product. Subsequently, this main intermediate is degraded by the evolution of aromatics and converted to be other products. Various variables of the process such as type of atmosphere, temperature and residence time can significantly determine the composition of a polyene material. Among degradation products produced in an inert atmosphere including hydrochloric acid (HCl) gaseous, liquid hydrocarbons and char, the main product is HCl which is able to be reused either in vinyl chloride production or other chemical processes.

In order to obtain high purity gaseous HCl, manufacturing process of vinyl chloride must be equipped with a gas purification unit. Hydrocarbon fraction from a process with steam atmosphere and high temperatures will be converted into the other compounds such as carbon monoxide, carbon dioxide and hydrogen. These by products are constructed a bench-scale bubbling fluidized bed to investigate some processing parameters on the product outcome. The chosen type of bed material is shown to be important for product outcome. By this reason, the large amounts of char and tar are produced from using catalytic inactive solid quartz as a bed material. While a great amount of conversion of PVC into the syngas are generated from using catalytic active material such as porous alumina (Mersiowsky, 2001).

2.3.1.3 Landfill

Both the stability of the PVC itself and the possible release of the various additives result in the dramatic concern about the fate of PVC products and their additives in landfills. Even if the behavior of other materials in landfills, a leaching and degradation was presumed, this was generally unsupported. Based on the supported findings, the assessment of PVC products and their additives relevant to landfill emissions should be done (Mersiowsky, 2001).

2.3.1.4 Incineration or Energy-recovery Techniques

One of the waste treatment processes associated with the combustion of organic substances in waste materials is called “incineration”. Commonly known as "thermal treatment", both incineration and other high-temperature waste treatment systems are. Ash, flue gas, and heat are converted by thermal treatment of waste materials. The inorganic constituents of the waste deliver a large amount of ash. Solid particulates or lumps carried by the flue gas are mostly established from this ash. The gaseous and particulate pollutants must be eliminated from the flue gas, before it is dispersed into the atmosphere.

In some electric power generation, incineration may be utilized as a source of heat. Nevertheless, additional concerns occurred when incineration of PVC with chemical additives, theses major parts of PVC by municipal and hospital waste are ignited in incinerators. Hydrochloric acid, a highly corrosive gas, is emitted by burning of PVC. Nonetheless, incineration regulations state and other resultant toxins must be removed and neutralized, it is found the troubling amounts of toxins leaking into the atmosphere. Some toxic elements, heavy metal such as cadmium and lead are still the component of this ash. Because of its cadmium and lead, the ash must be sent to controlled landfills.

However, space and groundwater contamination of controlled landfills are eventually concerned (http://greenliving.nationalgeographic.com/pvc-disposal).

The summary of recycling process (Table 2.6) indicates that there are 3 desire method which economically ways to handle post-consumer wastes due to the costs of disposing process. However, Mechanical recycling method is the acceptable and sustainable one which has applied to manage the accumulation of end of life PVC products.

Table 2.7 The comparative tabulated form of different approaches for the disposing of PVC wastes (Mersiowsky, 2001)

Method of Disposing	Sensitivity to impurities	Degree of pollution generation	Costs	recycled product(s)	Properties of the recycled material	Number of plants in operation around the world	Accepting by countries (during the recent decade, especially for developed countries)
Landfilling	Non-sensitive	Very high	Low-cost	No material recycled	–	Large	Non-acceptable
Incineration	Usually non-sensitive	Very high	Usually low-cost	Energy	Usually energetically not efficient	Large	Non-acceptable
Mechanical recycling	Highly sensitive	Low	Middle-cost	PVC	It is dependent on feed material and processing variables of recycling	Fair	Highly acceptable
Chemical recycling	Relatively sensitive	Usually low	Usually high-cost	Diverse raw materials	It is dependent on feed material and processing variables of recycling	Small	Low acceptable

2.4 Mass Flow Analysis (MFA)

Defined as a systematic assessment of the flows and stocks of materials within a temporal and spatial system, MFA, can be used to identify and analyze the flows of materials added to and removed from the system. MFA can identify environmental problems related to the material or formulating to the material or formulating efficient policy alternatives. Its outcome can be beneficial for analyzing the flows and stocks throughout the life cycles of target materials and for increasing the efficiency of material usage. Not only considering all resources or materials within the system but also focusing on individual materials such as metal, mineral and biomass conducts MFA (Park *et al*., 2010). Decision makers deeply know the metabolism of their region by the use of MFA. Regional processes and activities including construction, transportation, consumption and waste disposal are allowed to be the systematical connection with inputs and outputs. Exactly examination of the materials related to a given system (private household, company, region, city, etc.), the stocks and flows within this system and the resulting outputs from the system to others, MFA can get involved in. MFA highlights on loadings rather than concentrations so, it is different from other environmental management tools. According to its competency of examination the relationship between a region or city and its corresponding hinterland, MFA is considered to be a useful tool (Hendriks *et al*., 2010).

2.4.1 Methodological Foundations

MFA is composed of various steps shown below:

2.4.1.1 System Description

The investigated system is defined by boundaries in space and time. The relevant processes, goods and substances are defined and linked.

The selection of the processes is associated with identifying the most efficiently representative and descriptive key processes under investigation. Expression reality in a simplified way is the most crucial and essential steps of an MFA. Goods and substances are selected upon the study's nature.

Being capable of understanding the urban metabolism of a region, research-orientated projects which generally select interesting indicator materials, such as, the metal iron, lead, zinc and aluminum including carbon and nitrogen must be conducted. Highlighted on a specific environmental issue, more applied investigations with the selected specific problem materials must be done. On one hand, timber is focused as indicator materials in forestry management issues. On the other hand, nitrogen and phosphorus is concerned as indicator materials in eutrophication issues.

2.4.1.2 Data Acquisition

The flows and stocks of the defined system are determined by measurements, market research, expert judgment, best estimates, interviews and 'hands on' knowledge, etc.

2.4.1.3 Material Balances, Modeling and Scenario Building

Those processes without available data usually preform material balances indicating mass in = mass out. Figure 2.5 indicates the basic model of material flow accounting and analysis (MFA). Then, integration results into static or dynamic models must be accomplished. Assessment the impact of various measures on the regional stocks and flows of selected materials in view of environmental loads or resource depletion requires modeling different scenarios.

2.4.1.4 Interpretation

The interpreted results from MFA studies are taking important issues including loading quantities, the significance of stocks and the comparisons of results against environmental standards and/or sustainable indicators or other assessment approaches into account. Effectively policy making can make use of these

MFA results. By this way, communication between the relevant policy makers and stakeholders of water, energy, waste, transport, and environment management bodies, community groups, non-governmental organizations and representatives from neighboring regions, and etc. need to be held.

Workshops are probably needed for relevant stakeholders to determine what the impact of these results on each stakeholder and management group in the region and how the region should act toward these findings (Hendriks *et al*., 2000).

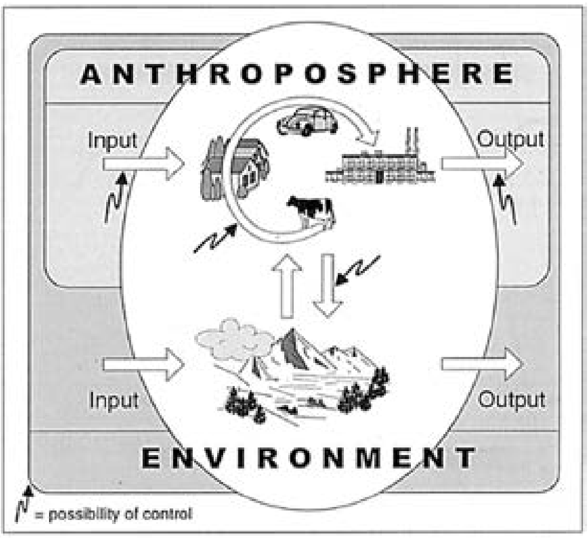

Figure 2.5 The basic model of material flow accounting and analysis (MFA) (Hendriks *et al*., 2000).

2.5 Consumer Behavior

A consumer is someone who makes demands in the market. Demands will lead to the production of commodity in the market. The producer would not producing without demands when there is no market for selling goods. The consumer behavior depends on demand of product, consumption of product and the consumer's equilibrium.

Demand of product is the willingness to buy a commodity at a particular price and a particular time. There are 3 components of demand including willingness to buy the product, willingness to pay for the product and the necessity of the product at a particular time.

Consumption of product is the use of goods and services to support human needs. Looking through all economic activities, consumption is both the beginning and the end of them. Consumption is important for any segment such as the government, business, household and society. Consumer’s equilibrium is a situation when a consumer derives maximum satisfaction from the given resources and a producer achieve the maximum profits (http://economicsmicro.blogspot.com).

2.6 Economic Factor

2.6.1 Gross Domestic Product (GDP)

Gross domestic product (GDP) is the monetary value of all goods and services produced within nation's geographic borders in a specific time period. Calculation of GDP can be based on not only the annual basis but also a quarterly one. All of private and public consumption, government outlays, investments and exports minus imports occurring within a defined territory are inclusively calculated to be GDP. In sum, GDP is the broadest quantitative measure of overall nation's economic activity. Figure 2.6 shows the trend of GDP in Thailand between 1961 and 2015.

Figure 2.6 The trend of GDP in Thailand from 1961 to 2015 (http://www.investopedia.com/terms/g/gdp.asp).

2.7 Literature Reviews on MFA Studies

2.7.1 PVC Product Flow in China

The rapid growth of polyvinylchloride (PVC) related industry in China would be certainly the cause of environmental problems. In 2013, Zhou and coworker studied the PVC metabolism by 3 following steps; (1) Illustrated in Figure 2.7 is the method of establishing dynamic models based on material flow analysis (MFA). Next step is (2) initiating calculation on lifetime distribution of different types of products and recycling in detail, and the last step is (3) Gaining the performances of waste emissions and accumulation as a function of raw material input and time. In this analysis, the developing trend of the PVC industry was studied and annual consumptions in future were predicted. Their analysis were based on system evolution theory and population development models. To calculate the annual emissions and accumulation after metabolism, tracking the amount of raw material input, existing form and process flow for a single year (2003), and over a longer period (from 1958 to 2048) in China need to be incorporated. Interestingly, considered by the effects of product structure, lifetime distribution, mechanical recycling, chemical recycling and incineration on waste output, the obtained result from this analysis showed that by the end of 2050, accumulation of PVC waste in china would be over 0.6 billion tons. Suitably modifying these factors could lead to decelerate of the product metabolism process. Otherwise, the effective solutions for this case were mechanical recycling and chemical recycling of PVC products.

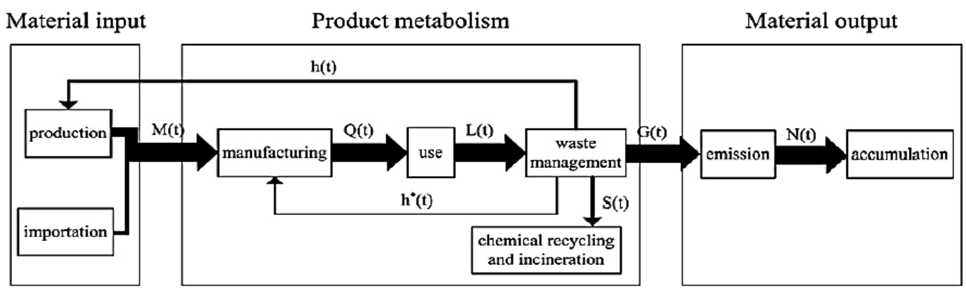

Figure 2.7 Framework of PVC products metabolism process (Zhou *et al*., 2013).

Based on each product purposes, Table 2.7 shows the three categories of PVC products in China including soft products, hard products and other products, and 11 sub-categories. Following the data from 1958 -2008 and using the model, the PVC consumption before 2050 was expected as shown in Figure 2.8.

With the assumptions and the available data life expectancy were obtained as shown in Table 2.7. The amount of emissions and accumulation of PVC waste produced in 2003 and discharge into the environment in following years were apparently viewed from the dynamic model. Only consideration of the input during a continuous period of time, instead of one year, they were not considered in this section, incineration, mechanical and chemical recycling seemed to be the effective processes. Based on the results of PVC consumption trend, analysis on multi-years input could be conducted by using the information of the metabolism of PVC products during 1958-2048.

In Table 2.7, the statistics of products structure and life expectancy for every stage was shown when the time was divided into different 4 periods.

Table 2.8 Structure and average life expectancy of PVC products in China during different periods of time. (Zhou *et al*., 2013).

Products classification	Product number (i)	Proportion (%)				Life expectancy
		1958–1991	1992–1997	1998–2003	2003–2050	
Soft products						
Subtotal		71	61.5	50.8	50.5	
Film	1	18.8	20.7	17.8	15.5	1
Cable material	2	16.1	12.9	4.7	4.4	15
Leather	3	15	13.7	12.1	13.2	5
Footwear	4	21.1	11.3	10.9	11.8	3
Others	6	0	2.9	5.3	5.6	3
Hard products						
Subtotal		19.4	29.8	42.3	44.5	
Pipe	7	5.7	8.1	12.8	16.6	30
Planking	8	11.4	14.8	12.6	9.2	10
Profile	9	2.3	3.9	8.9	9.7	15
Bottle	10	0	1.4	3.9	4.8	1
Others	11	0	1.6	4.1	4.2	5
Other products	12	7.6	8.8	7.0	5.0	3
Total		100	100	100	100	

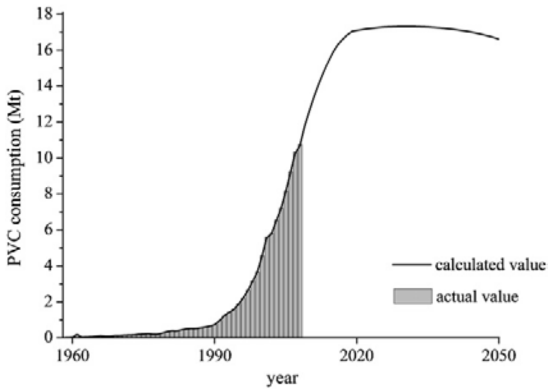

Figure 2.8 PVC consumption in China from 1958 to 2048 (Zhou *et al*., 2013).

The PVC waste emissions and accumulation in the environment after metabolism across the nine decades, without any considering recycling method and incineration, can be predicted annually.

It can be concluded from Figure 2.9 that the decreasing rate of emissions with the increasing rate of accumulation, finally both emissions and accumulation still significantly increase.

Reasonably predicted from parameters and assumptions in this study with in this model, the annual PVC waste emissions would be close to 16 Mt, and accumulation would exceed 600 Mt within 2050.

This apparent result summed up that the harmful consequences on human society and ecological system resulting from a large amount of waste discharged into our environment in the coming decades would exactly occur when the current trend of the PVC industry continued.

Consequently, this is the urgent time for establishing the appropriate measures specified technical support and policy guides. Moreover, the overdevelopment of the PVC industry and the reduction of the waste output should be avoided.

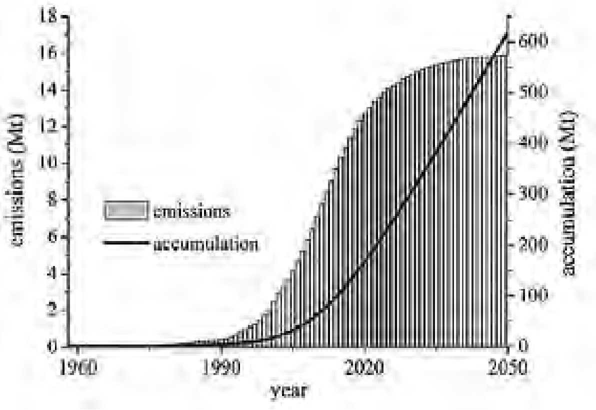

Figure 2.9 Annual emissions and accumulation of PVC wastes after metabolism in China from 1958 to 2048 (Zhou *et al*., 2013).

2.7.2 PVC Product Flow in Sweden

The topic of Kleijn *et al.* study in 2000 entitled today's stocks are tomorrow's emissions and waste flows. In figure 2.10 flows seemed to be under control could easily rebound resulting from the time lag introduced. Given example from this study suggested how to use signal processing in dynamic Substance Flow Analysis for the estimation of the future generation of waste and emissions from present societal stocks. The researcher designed the approach able to estimate the outflow of waste products from stocks on the basis of assumptions on the shape of the distribution describing the inflow of new products, the average life span of the products, and the life-span distribution. Furthermore, they simply applied the PVC's study case in Sweden as the theoretical case. The findings from this study are not only the delaying mechanisms of the stocks could make the outcome counterintuitive but also the chosen shape of the input-distribution function had the most impact on the predicted outflows. This findings is apparently seen in the case of possible fashion-type markets which is defined as the exponentially growth markets. Founded upon qualitative knowledge of the market holding different products, the choice of the shape of the inflow distribution can be. Results shown in Figure 2.11 indicated the height of the peaks and the time that they occur were subtly affected by the life-span distribution. The result from this study is considered as a normal distribution.

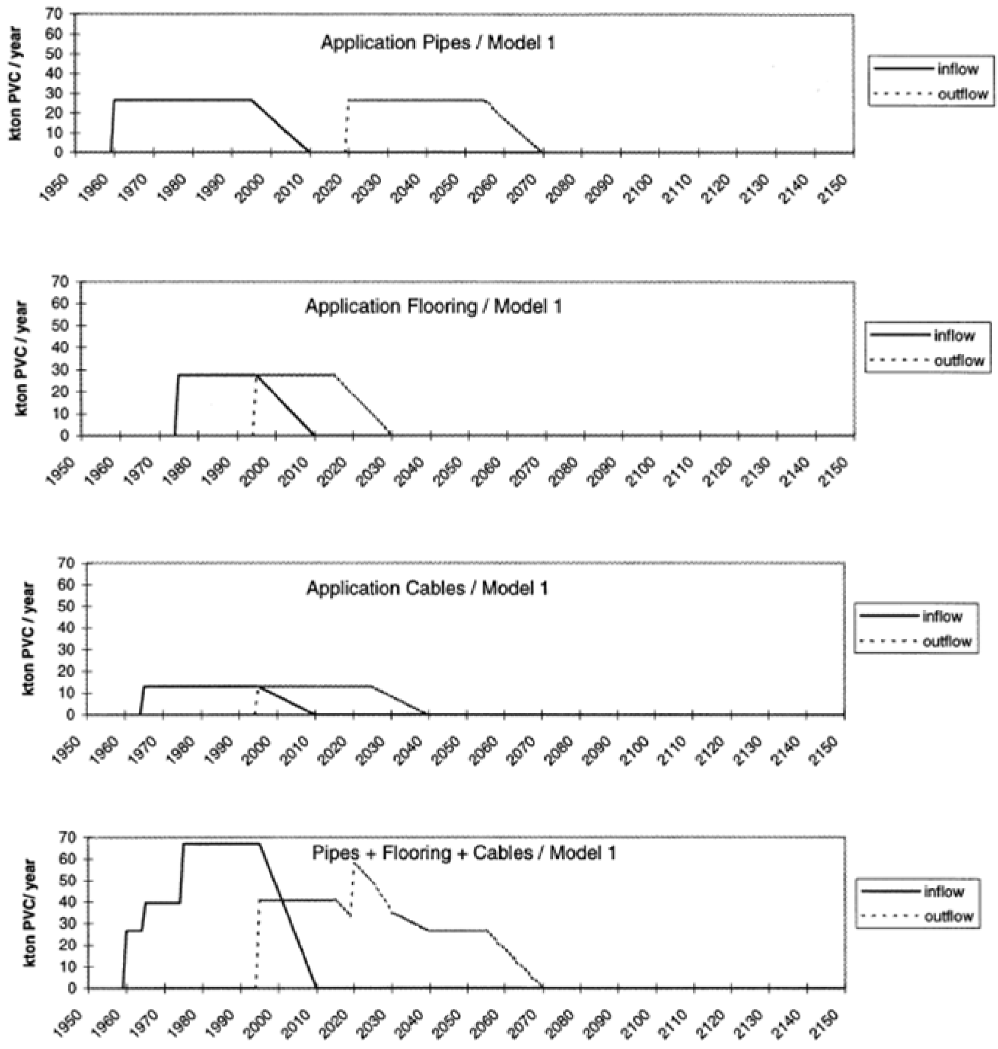

Figure 2.10 From top to bottom. 1a: PVC pipes, inflow and outflow; 1b: PVC flooring, inflow and outflow; 1c: PVC cables, inflow and outflow; 1d: pipes, flooring and cables combined, inflow and outflow, this figure shows the development of the inflow of new products and the outflow of waste of the three major PVC applications using model 1. (Kleijn *et al*., 2000).

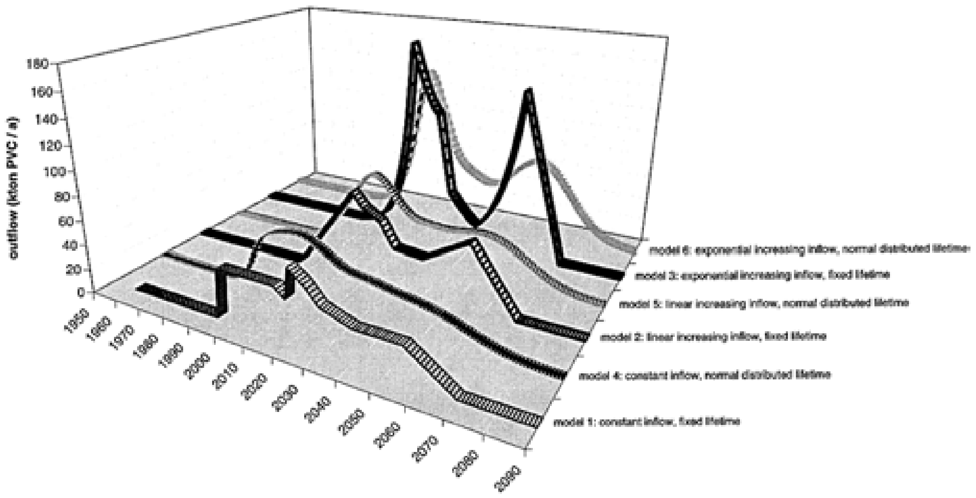

Figure 2.11 Assumed by different models showing the development of the generation of PVC waste as a result of the dynamics of the three major PVC categories (Kleijn *et al*., 2000).

2.8 LC-MFA of PVC Products in Thailand (Phase I Study)

This work performed a MFA of selected PVC products in Thailand based on a life cycle approach (LC-MFA) in order to assess the overview picture of PVC flow in Thailand. In this study, MFA was performed on selected PVC products (both hard and soft, including pipe, profile, cable, floor tile, floor covering, shoes, and hose) covering from materials and products production, use, transportation and disposal was shown in Figure2.10. It started from material flow-in (input) of the product from production into the consumption phase (Q_{in}) where the product was being used for certain period of time (n years), depending on its service lifetime. After its end-of-life, the product turned into waste and flows out of the consumption phase (Q_{out}) at certain period of years. The average service life values (year) and normal distribution of service life of target PVC products were shown in Table 2.8. The distributions were estimated based on the values reported by industrial association and literatures. Figure 2.12 was shown the MFA model in phase I. At this point, the material flow-out in each year (m^{th}) can be adjusted by using normal distribution applied to average service lifetime (n+j and n-j) and assume the average service lifetime is normal distribution curve (Figure 2.13).

The material flow-out (Q_{out}) from consumption phase at m^{th} year is then passed to the waste management phase where the PVC product is sorted out for further treatment. Three disposal technologies are used in the model in this study: landfill, incineration and recycle. The portion of material flow to each disposal technology can be identified by the user as a percentage (a%, b%, or c%). For recycle, mechanical recycling was assumed to be the main process used which involves cutting, cleaning, grinding, etc. For landfill, PVC waste is buried in the regulated sanitary landfill for such a long period (i.e., 10-20 years). After that, the landfill may undergo rehabilitation such that non-degradable PVC waste can be recovered and recycled. For incineration, the PVC waste is converted into a form of energy (heat).

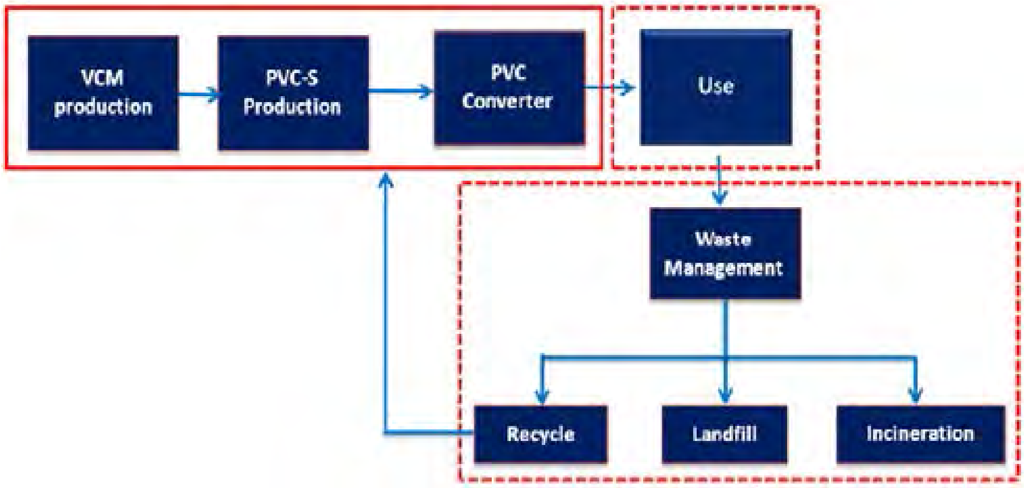

Figure 2.12 System boundary of phase I study (dashed line).

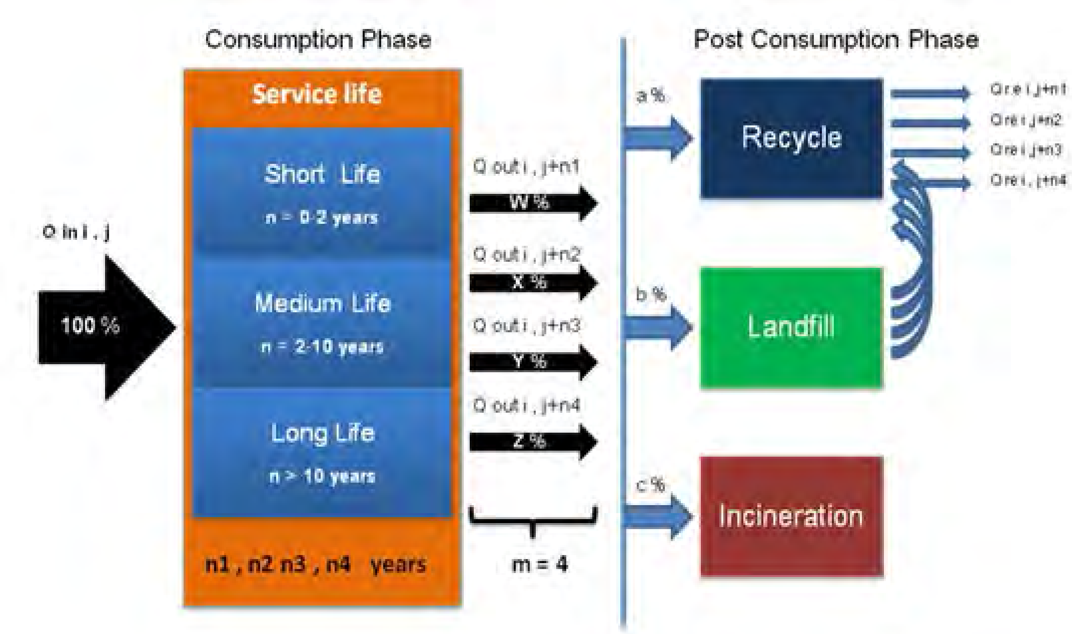

Figure 2.13 Generic model for MFA of PVC product developed.

Table 2.9 Average service life and distribution of PVC products

PVC products	Average service life (n = year)	Service life distribution (j = year)
Pipes & Fitting	35	+/- 15
Profiles	20	+/- 10
Cable	20	+/- 10
Floor tile	8	+/- 2
Floor covering	3	+/- 2
Shoes	3	+/- 2
Hose	3	+/- 2

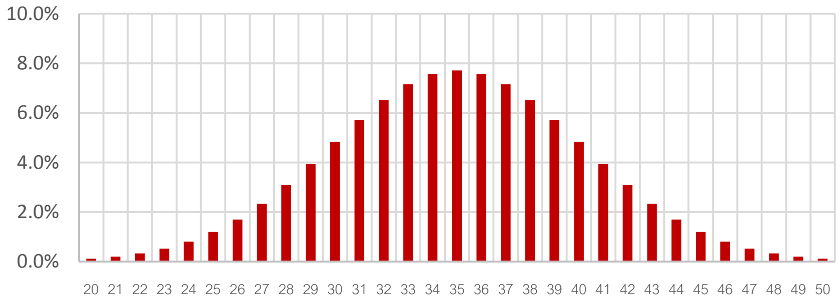

Figure 2.14 Normal distribution of service life of PVC products.

Actual production data in the past several years from manufacturers were used along with the annual domestic consumption of selected PVC products. The average service lifetime of individual product obtained from industrial association was used. After use period, normal distribution was applied to the average service lifetime of the products in order to estimate annual amount of product being discharged/disposed into the system and the environment at different years. For end-of-life, the PVC wastes were assumed to undergo either landfill, incineration or recycle at different amounts. Sampling in landfill was collected data based on standard quartering method from 11 landfill sites, covering all regions in Thailand However, pipe, profile, and floor tile were not found at all at these sites. Only little amount of PVC cable, hose and shoes (integrated with wood, rubber, fabrics and other plastics) were found, but in a very small amount. Moreover, researchers also visited to a major recycle shop in Bangkok: Amorn Recycle shop where all kinds of PVC wastes such as pipe and fitting, profile, cable, floor covering, shoes, hose etc. These PVC wastes are collected from several places around the country and they were believed that the amount of PVC wastes in this shop covers around 40% of recycled PVC being circulated in Thailand**.** Therefore the amount of overall recycled PVC in Thailand can be estimated by extrapolation from the amount of samples from this recycle shop.which stand for the total PVC recycle circulating in 2013 is approximately 31,140 tons**.**

This model was constructed and used to calculate and predict of the amount of PVC material flow in different pathways at different years in the past, present, and future was shown in Figure 2.15. The results from the LC-MFA model were compared with actual data collected at waste collection sites, disposal sites, and recycle shops (Table 2.9).

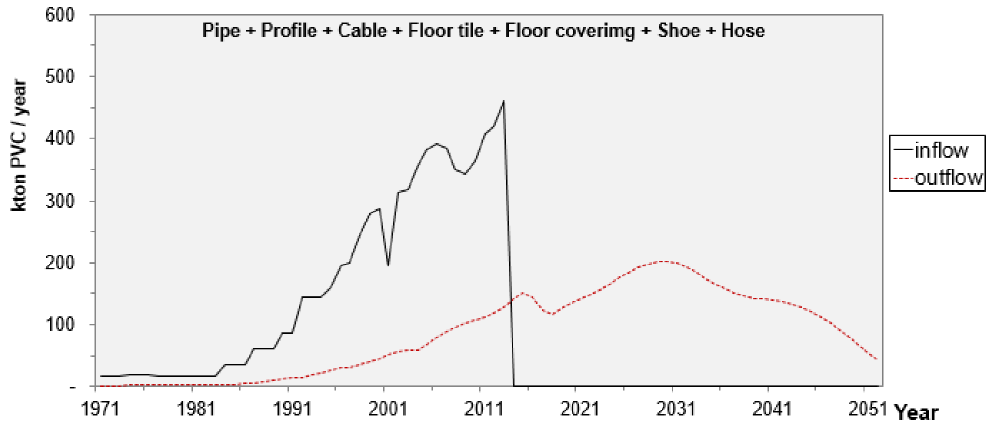

Figure 2.15 Annual waste outflows predicted from MFA model for multiple-year inputs of mixed PVC products.

Table 2.10 Materials balance based on MFA model

Products	Outflow from model (ton) (L(t))	Recycle (ton) (R(t))	Landfill (ton) (G(t))	Mismatch amount (ton)
Pipe and Fitting	8,833 (100%)	8,458 (95.75%)	0 (0.00%)	375 (4.25%)
Profile	15,447 (100%)	210 (1.36%)	0 (0.00%)	15,237 (98.64%)
Cable	38,595 (100%)	12,000 (5.87%)	2,036 (5.26%)	24,559 (63.63%)
Floor tile	10,316 (100%)	0 (0.0%)	0 (0.00%)	10,316 (100.0%)
Floor covering	26,425 (100%)	2,337 (8.84%)	0 (0.00%)	24,088 (91.16%)
Shoes	22,586 (100%)	3,875 (17.16%)	14,996 (66.40)	3,715 (16.44%)
Hose	6,733 (100%)	4,260 (63.27%)	2,143 (31.83%)	330 (4.90%)

It can be seen that some target PVC products such as pipe & fitting and hoses were being recycled at high percentage compared to the amount of outflow waste. In contrast, some other products were recycled at a relative small percentage. In addition, some of these products were not found very much at landfill sites. Therefore, there are unbalanced or mismatched amounts of the material flow. This could be due to several reasons such as error in extrapolation of recycled amount obtained from recycle shops, loss in the processes, or mismanagement of PVC wastes (Rodcharoen, 2014).

2.9 LC-MFA of PVC Product in Thailand (Phase II Study)

In phase II study, The study was performed on 7 selected PVC products (both hard and soft, including pipe, profile, cable, floor tile, floor covering, shoes, and hose) covering from use phase, transportation, and end-of-life which includes waste management, landfill, and recycle was shown in Figure 2.14.

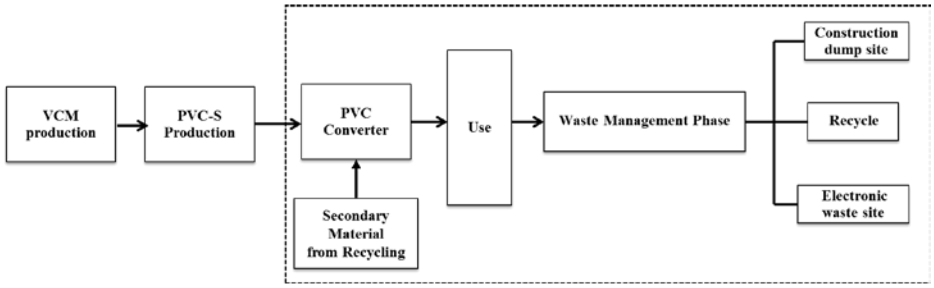

Figure 2.16 System boundary of phase II study (dashed line).

In this phase, they used the generic model and average service lifetime (normal distribution) same as phase I study but there are several things were added.

1. Updating data in 2014

Input the data of domestic consumption in 2014 in to the MFA model

2. Considering the losses during PVC recycling system

They included losses along the material flow from consumers to converters, losses accumulated about 30 percent (holdover 5%, transportation losses 10% and processing losses 15%) which was taken into account to estimate PVC recycle amount. The Losses during the recycling system was shown in Figure 2.17.

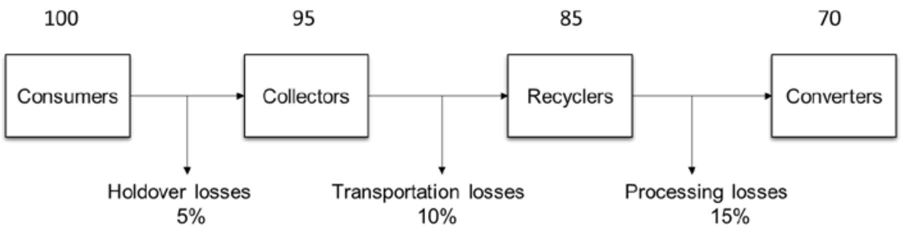

Figure 2.17 Losses during the recycling system in Thailand.

3. Collecting recycling PVC amount from converters and more recycle shops than phase I study.

A total of 20 companies, 14 recycle shops and 6 converters, were to be considered in this research.

4. Using a new estimation method of PVC recycle wastes call “crosscheck method”

Checking data of PVC recycle wastes between recycle shop and converters before extrapolation to estimate PVC recycling amount. The results of PVC recycling amount in 2013 (phase I) and 2014 (phase II) was shown in Figure 2.18

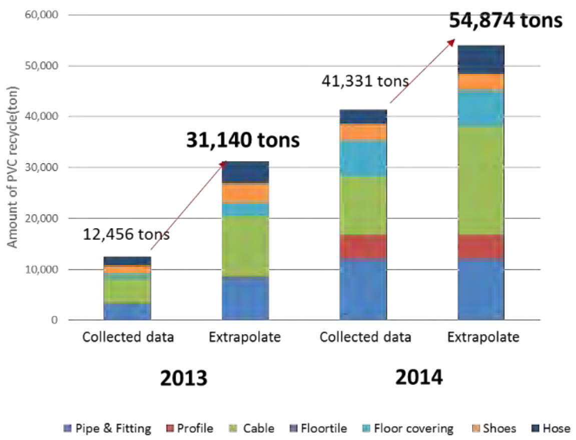

Figure 2.18 Comparing two extrapolation results in 2013 and 2014.

5. Investigating construction dump sites and electronic waste sites

In construction dump sites, the volume of PVC waste products (pipe & fitting, floor tile, profile, and cable) is relatively small compared to other demolition wastes that were found.

In electronic waste sites where the villagers in these areas have a business in sorting metal and valuables from electronic wastes for trading in Burirum province. they found many kinds of electronic appliances such as refrigerators, cathode televisions, washing machines, electric fan, it has some parts of PVC such as small cable which were burned to get the metal inside which affects both health and environment. All this to assess the overview picture of PVC flow in Thailand precisely (Nakem *et al.*, 2016).

CHAPTER III
METHODOLOGY

3.1 Software and Equipment

3.1.1 <u>Equipment</u>

- Desktop computer (Intel Core i5, Window 7)

3.1.2 <u>Software</u>

- Microsoft Office 2013

3.2 System Boundary

In this MFA study, the system boundary was set to cover all processes after the PVC products were produced and distributed to the market. The study focused only on domestic consumption. Figure 3.1 shows the schematic diagram entire life cycle of PVC product. However, the system boundary set in this study covered only use phase, transportation, and end-of-life which includes waste management, recycle (as indicated by dashed line).

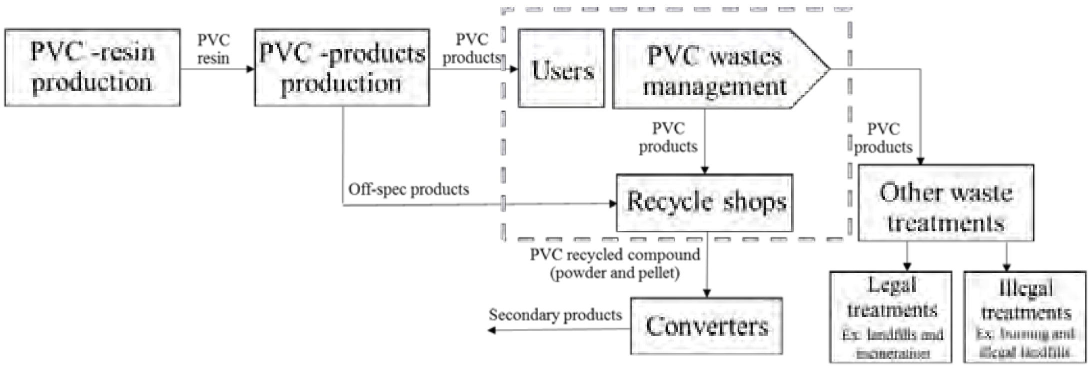

Figure 3.1 System boundary of this study (dashed line).

3.3 Generic Model for MFA of PVC Products and Adjustable Parameters

A generic model of MFA for PVC product is shown in Figure 3.2. The MFA model indicated material flow-in (input) of the product from production into the consumption phase (Q_{in}) where the product is used for a given period of time (n years), depending on its service lifetime. After its lifetime, the product turns into waste and flows out of the consumption phase (Q_{out}) at certain period of years. We used average service lifetime reported by industrial association and literature. At this point, the material flow-out in each year (m^{th}) can be adjusted by using distribution applied to average service lifetime (n+j and n-j).

The material flow-out (Q_{out}) from consumption phase at m^{th} year is then passed to the waste management phase where the PVC product is sorted out for further treatment. Basically, there are three disposal technologies were used in waste management: landfill, incineration, and recycle. However, this study focuses on recycling system and looks over the construction dump sites and E-waste sites where some PVC wastes might be disposed. For recycling method, mechanical recycling was assumed to be the main process used which involves cutting, cleaning, and grinding. For construction dump sites, PVC waste is buried in the private landfill as land reclamation. After that, PVC products might be sorted and taken to recycling system.

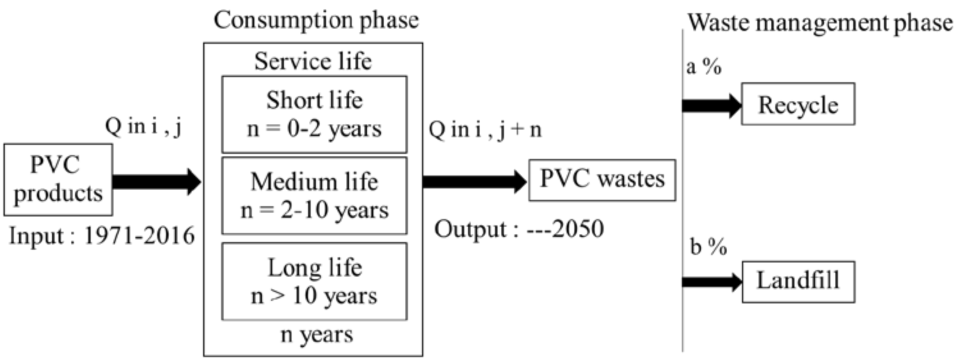

Figure 3.2 Generic model for MFA of PVC products.

3.4 Average Service Lifetime and Consumer Behavior & Economic Decision

The average service lifetime of each PVC product selected in this study and its distribution (+/- years) are shown in Table 3.1. It was designated by PVC industrial association and manufacturers of each PVC product in Thailand compared with values reported in literature (Zhou *et al*., 2012).

Table 3.1 Average service lifetime and service life distribution

PVC products	Average service lifetime (n)	Service life distribution (y)
Pipe & Fitting	35	±15
Profile	20	±10
Cable	20	±10
Floor tile	8	±2
Floor covering	3	±2
Shoes	3	±2
Hose	3	±2
Sheet & Film	3	±2

Once this is set, the outflow of specific PVC product in each year (m^{th}) can be calculated by the model based on normal distribution and Gross Domestic Product (GDP) distribution following the condition in Figure 3.3.

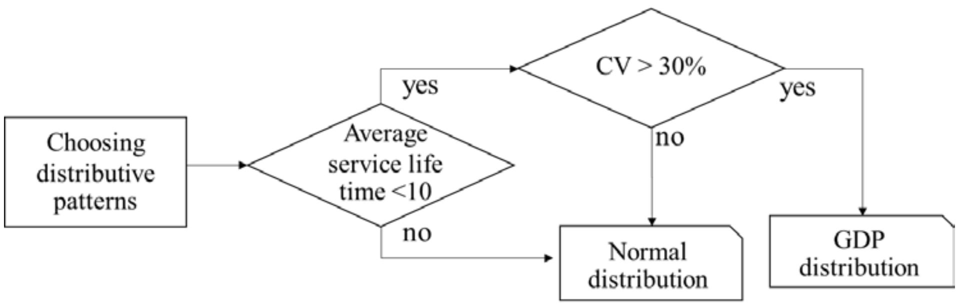

Figure 3.3 Choosing distributive condition in the MFA model.

Figure 3.3 shows the choice of decision for distributive patterns in outflow calculation. Starting with, considering average service lifetime of each product, if the products have the service lifetime lower than 10 years, the consumer behavior and economic decision will be taken into consideration. Second step, calculating the coefficient of variation (CV) by annual GDP of m^{th} , the CV more than 30% are considered meaning that it has a reasonable variability of economic which causes consumer decision to buy and discard products. To illustrate, an increase in the GDP has a significant impact on consumer decision to buy a new product and discard their old products although it still is usable. For this reason, the GDP distribution is used to estimate outflow in this case. Meanwhile, the CV lower than 30%, the outflow is calculated by a normal distribution as same as the products which have service lifetime more than 10 years. This because long service lifetime PVC products are referred to construction materials e.g., pipe and cable. Hence, it does not depend on consumer decision.

3.4.1 <u>Coefficient of Variation (CV)</u>

The coefficient of variation (CV) is defined as the ratio of the standard deviation (σ) to the mean (μ). $CV = \frac{\sigma}{\mu}$
It shows the extent of variability by the mean of the population.

The coefficient of variation should be computed only for data measured on a ratio scale. In this study, the CV used to signify economic variability by annual GDP in Thailand. To illustrate, the inflow in the year 1984 of floor covering (n = 3, y $=\mp 2$) would have outflow from 1985 to 1989, GDP from 1985 to 1989 were calculated to CV.

3.4.2 <u>GDP Distribution Normal Distribution</u>

The CV higher than 30%, the outflow was calculated by GDP distribution which depended on average service lifetime (n), service life distribution (y) and annual GDP. The example of normal distributive pattern between 1985 and 1989 is showed in Figure 3.4

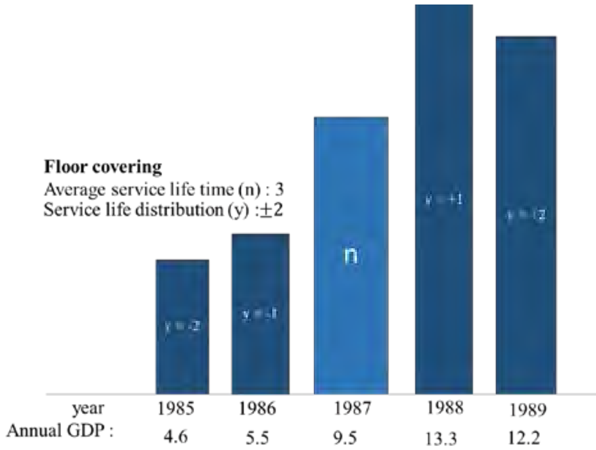

Figure 3.4 The example of GDP distributive pattern.

3.4.3 <u>Normal Distribution</u>

The CV lower than 30%, the outflow was calculated by a normal distribution which depended on average service lifetime (n) and service life distribution (y). The example of normal distributive pattern is showed in Figure 3.5

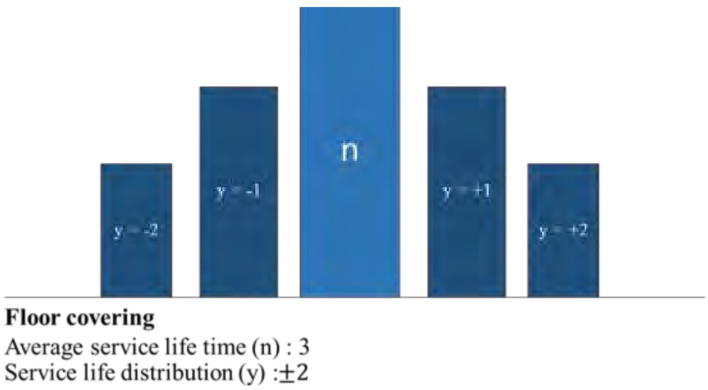

Figure 3.5 The example of normal distributive pattern.

3.5 Data Collection

This project used domestic consumption of years 1971 to 2010 obtained from the previous research. Moreover, the updated dataset domestic consumption from 2011 to 2016 provided by the ASEAN Vinyl Council (AVC)were conducted to obtain the data that are necessary for running and testing MFA model. Group meetings between the research team and AVC was taken place during project's period in order to identify and ensure with the data being used in MFA model, such as the amount of domestic consumption of PVC products, average service lifetime of PVC products and service lifetime distribution of PVC products after interpreting the results. The sources of data are identical with the previous research as shown in Table 3.2

3.5.1 Domestic Consumption of PVC Products

In this study, pipe, fitting, profile, cable, floor tile, floor covering, shoes, hose, and sheet & film were selected as model PVC products to represent both hard and soft PVC products used in Thailand. Most of the PVC products used come from two pathways: domestic production and importation.

3.5.1.1 Domestic Production

For domestic production, data of domestic PVC resin collected from ASEAN Vinyl Council (AVC). Most of data were received from two major PVC producers in Thailand; Thai Plastic and Chemical Public Company Limited (TPC) and Vinylthai Public Company limited (VNT), and the period of PVC resin cover 1971 to 2016.The proportions of PVC resin use in each application are shown in Table 3.3.

3.5.1.2 Imported Products

The data of imported PVC products were obtained from the Custom Department of Thailand by tracking from the harmonized code. However, the obtained data posed some limitations; for example, the available data for PVC import are only from 2007 to 2012, and some of the data do not cover all of our target products. However, it can be seen that the imported PVC products are relatively small when they are compared with the domestic products. So we can neglect this number when we test the MFA models.

Table 3.2 Sources of data

Phase	Process	Source
PVC product Production (Domestic)	Pipe and fitting	AVC, major manufacturers, and MTEC
	Profile	
	Cables	
	Other products	
Consumption or use (Domestic)	Hard PVC products	AVC, major manufacturers
	Soft PVC products	AVC, major manufacturers
End-of-life	Recycling	PVC recycling shops and converters
	Landfill	Electronic waste sites

Table 3.3 Proportion resin used in each PVC applications (AVC, 2013)

Application	Percentages
Pipe & Fitting	38.68%
Cable	10.57%
Floor covering	9.09%
Profile	8.56%
Shoes	2.77%
Hose	1.01%
Floor tile	0.65%
Sheet & Film	21.61%
Artificial leather	3.05%
Auto	1.99%
Medical	1.75%
Others	0.26%
Total	100.00%

The PVC products are mainly produced from several of material in which major ingredient is a polyvinyl chloride. Other ingredients are including plasticizers, stabilizers, pigments, lubricants, and functional additives which may be compounded with a PVC resin. Each of additional ingredient varies by compounding formula. The formulations of compound used in this study were obtained from the study of European Commission (2004) and AVC (2014) as shown in Table 3.4. After compounding process, the PVC compounds will be converted to PVC products.

Table 3.4 Formulations of PVC compound in target PVC products

PVC applications	Resin	Additives	Product
Pipe & Fitting	98%	2%	100%
Profile	85%	15%	100%
Cable	42%	58%	100%
Floor tile*	26%	74%	100%
Floor covering	42%	58%	100%
Shoes*	50%	50%	100%
Hose*	61%	39%	100%
Sheet & Film	42%	58%	100%

Source: European Commission (2004) and *AVC (2014)

3.6 Off-spec PVC Products Estimation

To adjust the PVC products by taking the off-spec PVC products into account. The reason for this is that off-spec PVC products from industrial wastes are pre-consumer wastes as illustrated in Figure 3.6 which are not included in scopes of this study

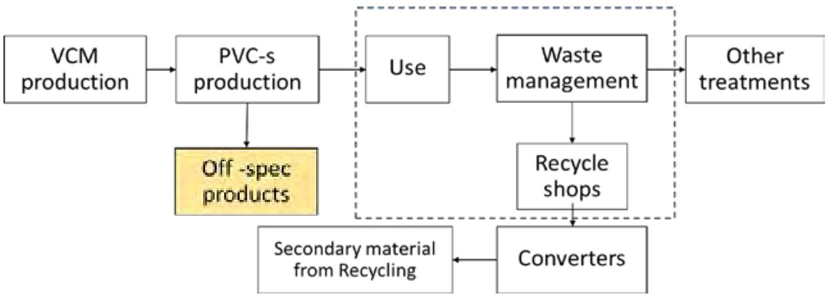

Figure 3.6 The system boundary with off-spec products position.

The off-spec products was estimated in percent by the industrial wastes report in 2015 from Department of Industrial Works in order to find the amount of off-spec products from PVC industrial wastes from main factories that produce the eight target PVC products. The result is compared with total productions of each application and calculating into percent before taking into account of the model.

3.7 Data Collecting Document

This document used to get information from recyclers and converters in order to increase preciseness, for instance, the source of wastes, type of wastes (pre or post-consumer), type of products and comments. The data collecting form was sent by either email or filled by recyclers and converters on the visiting. Figure 3.7 shows collecting form used in this study.

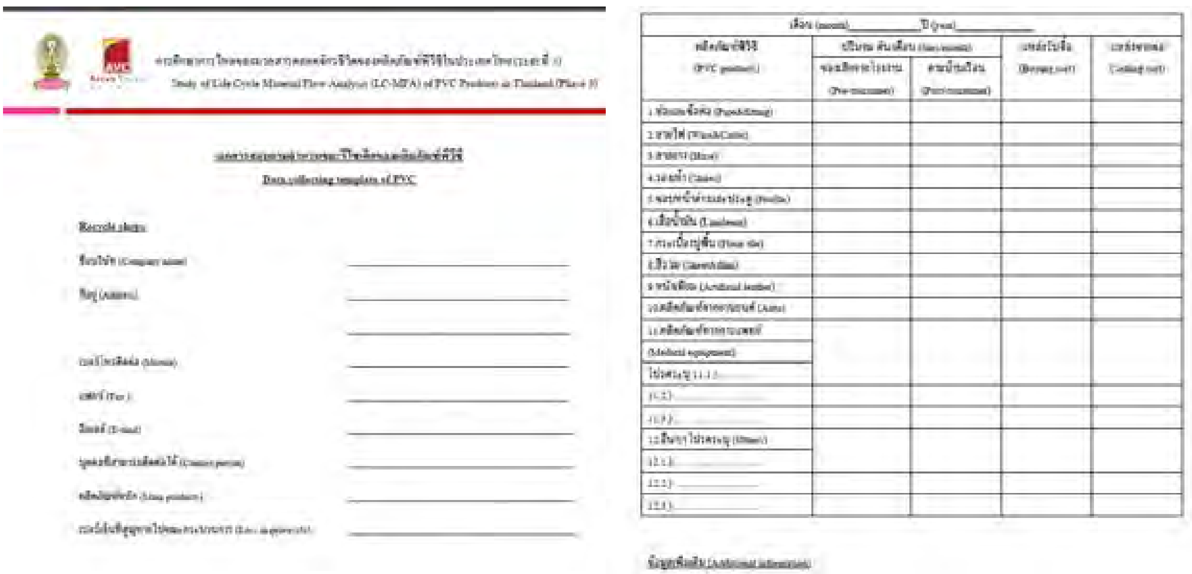

Figure 3.7 Data collecting document**.**

3.8 Site Visits

To assess data regarding the amount of wastes or materials flow of PVC products that out of the consumption phase after service lifetime, it was to visit several waste treatment factories, waste collection centers, PVC recyclers and converters. It should be noticed that the data collected in this phase represent the amount of PVC waste in 2015 and 2016.

3.9 Contact by Phone & Email Conversation

The assessing data, regarding the amount of wastes or materials flow of PVC products that out of the consumption phase after service lifetime from recycle shops and converters visited in phase III but not convenient to visit in this year were collected via phone and email.

3.10 Cross Cheek Method

The additional number of r recycle shops and converters added to obtain more representative data fort better result accuracy. This new estimation method is based on extrapolation of the eight target products as shown in Figure 3.8. The amount of recycled wastes in each product is obtained from recycle shops (A, B, C, D) and then the information is cross-checked by data from converters (G, H, I). Consequently, the new method provides a remarkable precise amount of recycled wastes

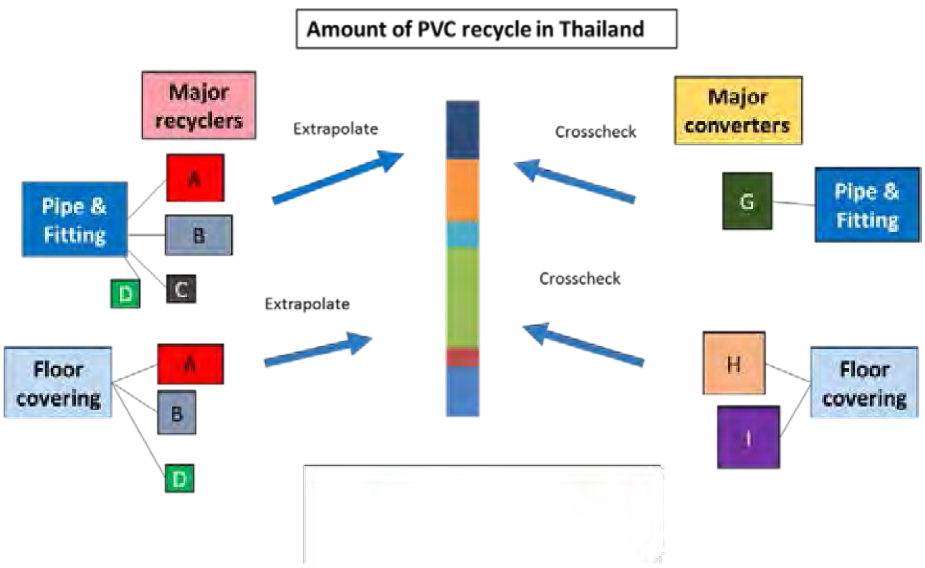

Figure 3.8 Cross cheek method.

3.11 Model Testing and Scenarios Analysis

In this model, some adjustable parameters are identified including:

1) PVC input (production)
   - Based on multiple-year inputs
2) Output (post consumption/waste)
   - Average service life
   - Normal and GDP distributions

3.12 Assumptions

1. PVC products consumption in the use phase is equal to PVC products production in the manufacturing phase.
2. Stock of PVC products production is not considered in this study, so that PVC products will enter use phase in the production year.
3. PVC products importation is neglected in PVC metabolism because its quantity is relatively small.
4. All products which enter to PVC metabolism are on the specification and standard of each product.
5. The residence time of PVC products in the using phase depends on the average lifetime and lifetime distribution.
6. In this study, only two waste management technologies are considered the end of life of PVC products which are: recycle and landfill in the year which PVC wastes are released.
7. It is assumed that recycled PVC from mechanical recycling in pipe & fitting and cable is not used to reproduce the original product.
8. The exported products are out of boundary, only domestic consumption is considered as an input to the model.
9. MFA model is focus on post-consumer wastes, which could cause the PVC mismanagement and environmental concern, in term of pre-consumer wastes should be handle properly with waste management regulations.

CHAPTER IV
RESULTS AND DISCUSSION

In this study, the results were divided in five sections which consisted of data collection, updating the amount of PVC recycled products in 2015 and 2016, off-spec products estimation, material flow analysis results and recycle amount compare to MFA model respectively. As can be seen from the methodology, section 3.2, the boundary was set to cover processes after the PVC products were produced and distributed. The relation between result sections and scopes is given in Figure 4.1 to make it easier to understand the overview of this work.

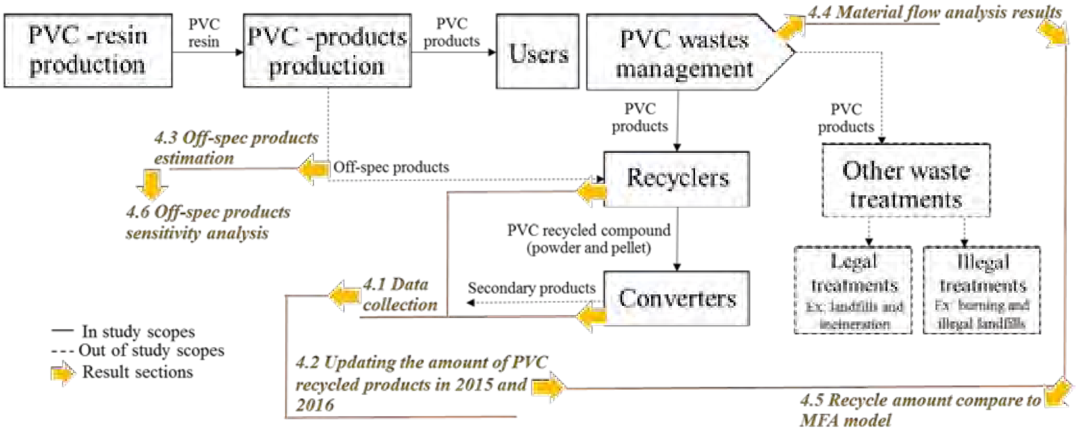

Figure 4.1 The relation between result sections and scopes of this study**.**

4.1 Data Collection

The data were collected from 22 companies including 18 recycle shops and 4 converters to find the route of PVC products after using in recycle businesses and to update the amount of PVC recycled products in 2015 and 2016 in Thailand by visiting and phone & email contact. The lists of recycle shops and converters are given in Table 4.1 and 4.2

Table 4.1 List of Recycle shops

Product	Company
Pipe & Fitting	Aor. Chareonsub*, Sa-ne PVC*, HV plus, Yingchareonsub PVC and LSA plastic*
Floor covering	Corporation (K'Neung)*, Nimcraft, Aor. Chareonsub, HV plus, Dura-inter, Yingchareonsub PVC and Corporation (K'Krit)
Cable	888Lion*, Aor. Chareonsub, HV plus, LSA plastic and Corporation (K'Krit)
Shoes	888Lion, Aor. Chareonsub*, HV plus, Yingchareonsub PVC*, LSA plastic, Corporation (K'Foo), Corporation (K'Krit) and Corporation (K'Komsak)
Hose	Corporation (K'Neung), Aor. Chareonsub*, HV plus, Dura-inter, Yingchareonsub PVC, Corporation (K'Thongsook) and Corporation (K'Krit)
Sheet & Film	Corporation (K'Neung), Nimcraft, Corporation (K'Foo)*, Corporation (K'Thongsook), Corporation (K'Komsak) and Corporation (Suwan)
Profile	Nimcraft, Dura-inter and Yingchareonsub PVC
Medical products	Nan Hospital
Artificial leather	Corporation (Changzoon), Corporation (Chi) and Corporation (Suwan)
Other plastics	BR recycle

* represents the main recycle shops in each product

Table 4.2 List of converters

Product	Company
Sheet & Film	MPI, HV plus and KHI
Floor Covering	KHI, TPI, HV plus and MPI

4.1.1 Company Details

4.1.1.1 New Companies

In phases III study, we investigated the new companies for 11 companies following this:

4.1.1.1.1 Corporation (K'Neung)

The recycle shop is located in Samut sakhon. This company trades floor covering as major recyclate. Sheet & Film and hose are minor products. This company claims that nowadays floor covering can be recycled in the large amount, collected from household, collector and sell to the recycle shop, but the rate of recycling floor covering from converters depends on economic situation. However, this shop still buys floor covering continuously every month especially in the month that has low price of floor covering in order to make more profit in the future. Figure 4.1 shows large amount of floor covering waiting for recycling process

Figure 4.2 Floor covering waste stock for recycling process.

4.1.1.1.2 Nimcraft

Located in Nakhon Pathom, This recycle shop trades many PVC products before compounding to recycling power, mixing several products and adding calcium carbonate as an additive, after that recycling power is sent to MPI converter, for instance, Floor covering, Profile and Sheet & Film. They can separate PVC shee t& film from carpets by the heating method but we found that a large amount of sheet & film came from off-spec products or industrial wastes which are pre-consumer products which is excluded in this study. Fortunately, the owner can identify both pre-consumer and post-consumer.

4.1.1.1.3 BR Recycle

This recycle shop is located in Buriram. They usually trades plastic bottles as shown in Figure 4.3 which are low density polyethylene (LDPE), high density polyethylene (HDPE), and polystyrene (PS),no PVC products in this shop. The process in begin with buying plastics bottles from collectors after that the bottles are separated by color and plastics types then grinding into scrap and offering for sale. Figure 4.4 shows plastic scrap after grinding process.

Figure 4.3 Recycling plastic bottles from BR shop.

Figure 4.4 Plastic scrap after grinding process.

4.1.1.1.4 Nan Hospital

Nan hospital has reasonable medical wastes management call “Recycle bank” for collecting and separating medical wastes, for instance, medicine bottles, saline bottles etc. as shown in Figure 4.5. From group meeting with medical team, they claimed that all wastes in the recycle bank were uninfected, therefore, it can recycle. In addition, the medical team desired to launch the dialysis bags recycling campaign because it have high consumption about 81,600 pieces in Nan and most of wastes did not handle properly now. Although, nowadays, some of dialysis bags in Nan have reused as the bags on Kiddee projects, it uses in relatively small amount comparing with the total.

Figure 4.5 Medical wastes from recycle bank in Nan hospital.

4.1.1.1.5 MPI

This company is a converter, located in Nakhon Pathom, they buy recycling powder to reproduce secondary grade products. They told that the positive thing of use recycling material was cheaper than PVC resin however the recycling power was hard to operate and cause a lot of processing wastes. From price competition, they must reduce cost as much as possible and recycling material was good solution. Although recycling materials can reduce a production cost, some of products which need high quality cannot use recycling materials.

4.1.1.1.6 KHI

KHI Company is a converter, located in Samut Sakhon. They have used recycling recycled compound since it was establish. Usually, they use mixing recycled compound between soft and hard PVC products and adding Calcium carbonate as an additive before blending with PVC resin. They told that not only PVC resin cost had fluctuation but also recycling compound especially sheet & film and linoleum products.

4.1.1.1.7 LSA Plastic

This shop was discovered by Facebook, located in Samut Sakhon. They is one of major recyclers in Thailand. They trade pipe & fitting, cable and shoes, post-consumer. It has possibility to visit their company in the next phase.

4.1.1.1.8 Corporation (K'Krit)

This shop is located in Samut Sakhon. The owner trades shoes, hose, cable and floor covering. The owner was inconvenient for meeting at company but be delighted to give information from phone conversation.

4.1.1.1.9 Corporation (Changzoon)

This company, located in Chonburi, revealed that they traded artificial leather for 40 tons per month. The owner is inconvenient for meeting at company.

4.1.1.1.10 Corporation (Suwan)

This company traded artificial leather 3 tons per month in the past but now they are out of business because of from converter, they told that in the past artificial leather used to reproduce floor covering.

4.1.1.1.11 Corporation (K'Thongsook)

This shop is located in Bangkok. This middle scale company deals with corporation (K'Neung) in order to sell hose and sheet & film to make profit.

4.1.1.1.12 Corporation (Chi)

This company traded artificial leather 5 tons per month in the past but now they are out of business because of no ordering from converter. They said that artificial leather was hard to separate plastic from fabric, contaminate, make problem in reproduction.

4.1.1.2. Other Companies

The other companies were visited in Phase II and in this we went to visit again to update data of PVC recycled products which had 9 companies following this:

4.1.1.2.1 888Lion

This recycle shop is located in Lum Luk Ka, Pathum Thani where used to visit in phase I and phase II , the shop is re-visited in order to get more updates information on PVC recycling in 2015 and 1016. This company trades cable as major and shoes as minor recyclate. They have the ability to separate cable and wire even very small cables as shown in Figure 4.6 .In addition, they can convert cable and shoes into PVC recycling pellet by extrusion machine after selling into secondary compound as shown in Figure 4.7 .Furthermore, we found industrial waste cables from an extrusion process, entrepreneur claimed that it was 20% of total amount. (Figure 4.8)

Figure 4.6 Separated small cables.

Figure 4.7 PVC recycling compound.

Figure 4.8 Industrial cable wastes from extrusion process.

4.1.1.2.2 Aor. Chareonsub

This is a major recycle shop located in Pathum Thani which was visited in Phase I and Phase II, the shop was re-visited in order to update information on PVC recycling in 2015 and 1016. This company trades both rigid and soft products such as pipe & fitting, cable, floor covering, shoes and also hose. Pipe & Fitting is the major recyclate and other products are minor reyclate. They compounded pipe & fitting into powder before selling to converters. In addition, all of PVC products in this recycle shop come from consumers. Figure 4.9 shows recycling PVC wastes in Aor. Chareonsub.

Figure 4.9 Recycling PVC wastes in Aor. Chareonsub.

4.1.1.2.3 Sa-ne PVC

This company is located in Nonthaburi which was visited in Phase II, the shop was re-visited in order to get PVC recycling in 2015 and 1016. They trade only pipe & fitting combining materials with Aor. Chareonsub around 50% of the total. The wastes are sent to a grinding process and the PVC powder was sold to different markets such as local Thai converters and also exported to neighboring countries such as Cambodia, depending on economic gains. In phase III visit, we found their business seem not good because of lower ordering from MPI converter, the main reason is they has higher price comparing with the competitor.

4.1.1.2.4 HV-plus

This company is located Samut sakhon and can be recycler and converter because they collected PVC wastes by themselves after that compounding then reproduce into floor covering. The collected PVC wastes are pipe & fitting, cable, floor covering, shoes and hose which came from consumers. Figure 4.10 shows reproduced floor covering.

Figure 4.10 Reproduced floor covering from Hv plus.

4.1.1.2.5 Dura-inter

This company is located in Bangkok which was visited in Phase II, the shop was re-visited in order to updates on PVC recycling in 2015 and1016. The shop cooperates with the PVC recycling factory Q – Plus. The shop produces PVC powder using several recyclates, profile (major recyclate), hose and floor covering. Some of products come from off-spec product (pre-consumer). Fortunately, the owner can identify both pre-consumer and post-consumer.

4.1.1.2.6 Yingchareonsub PVC

The shop is located in Saraburi where was visited in phase II. The company collected the PVC post- consumer wastes from Saraburi and nearby provinces and process them (Figure 4.11) with crushing to scraps as shown in Figure 4.12. After processing, wastes will be sent to converters located in the middle part of Thailand. They trades pipe & fitting, cable, floor covering, shoes, profile and hose.

Figure 4.11 Crushing process to gat recyclate scrapes.

Figure 4.12 The PVC scrapes after crushing process.

4.1.1.2.7 Corporation (K'Foo)

This shop, where was visited in phase II, is located in Samut Sakhon. This small scale company deals with soft products such as sheet & film and shoes which are divided into pre-consumer wastes (90 percent) and post-consumer wastes (10 percent).

4.1.1.2.8 Corporation (K'Komsak)

This company is located in Samut Sakhon, where was visited in phase II, The company is both a recycle shop selling post-consumer wastes to floor covering converter (Thai Plastic Industries) and a shoes manufacturer producing PVC shoes for export by using PVC resin and production wastes from industries such as artificial leathers and labeling films.

4.1.1.2.9 TPI

This company is converter, located in Nakhon Pathom They order recycling compound from corporation (K'Neung), corporation (K'Foo) and corporation (K'Komsak). This factory produce floor covering, they said that they use recycling compound to reproduce floor covering because of price. From recycling material price now floor covering is cheapest 7 baht followed by calendaring film and sheet by 12-15 baht and transparent film 15-20 baht comparing with PVC resin 31 baht. Therefore, if they can increase ratio of recycling material, the cost will decrease. Moreover, they import recycling material because of lower price than Thailand.

After investigating, it can be clearly seen that the recycling rate will reduce around 20% in 2016. Most of recyclers claimed that their ordering from converter was decreasing about 10-40%. The reason of this came from various reasons for example, oil price reduction so PVC resin price also drop and cannot compete the price with China.

4.1.2 Route of Recycling Businesses

After collecting data, we that the route of PVC products in recycling businesses could be divided to five routes as shown in Figure 4.13 and Table 4.3 indicates list of companies in different five routes.

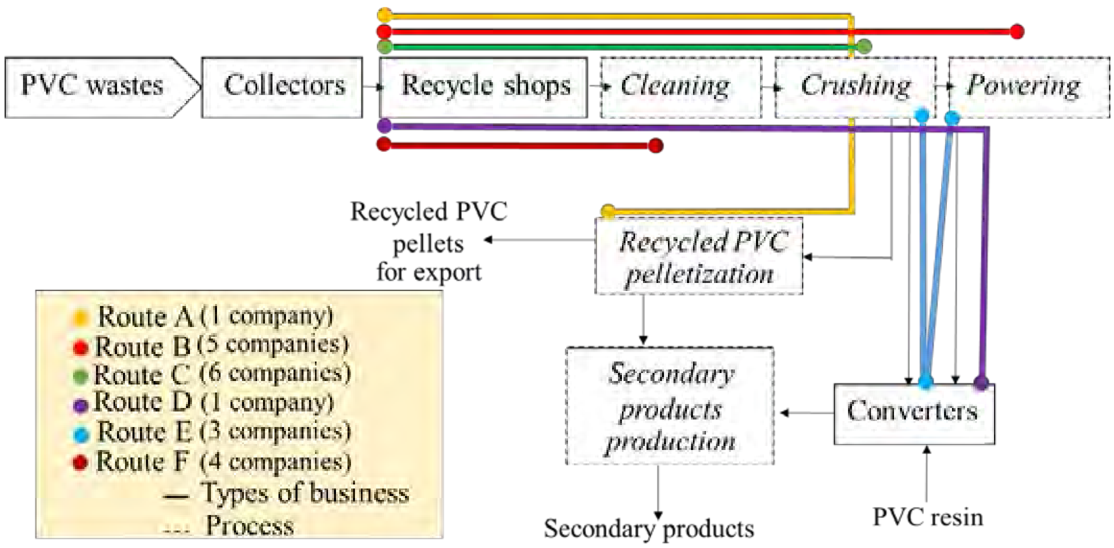

Figure 4.13 The routes of PVC products in recycle businesses.

Table 4.3 List of companies in different five routes of recycling businesses

Route of businesses	Company
Route A	888Lion
Route B	Aor. Chareonsub, Sa-ne PVC, Dura-inter, LSA plastic and Nimcraft
Route C	Corporation (K'Foo), Corporation (K'Neung), Corporation (K'Krit), Corporation (K'Komsak), Yingchareonsub PVC and Corporation (Changzoon)
Route D	HV plus
Route E	MPI, TPI and KHI
Route F	Nan hospital, Corporation (K'Thongsook), Corporation (Chi) and Corporation (Suwan)

4.2 Updating The Amount of Recycled PVC Products in 2015 and 2016

Data collection are gathered based on site visit and interrogation by phone & email. The amount of recycling PVC wastes are illustrated in Table 4.4. The primary data were collected from the production records of the manufactures as well as the secondary data were collected by forecasting from production data obtained from the owners. The amounts of recycled PVC wastes in 2015 and 2016 were approximated by the crosscheck method as mentioned in the methodology, section 3.10.

Table 4.4 The amount of recycled PVC products in 2015 and 2016

Applications	Year 2015	Year 2016
	Estimated data (ton)	Estimated data (ton)
Pipe & Fitting	14,676	13,106
Floor covering	11,712	7,493
Cable	13,051*	12,321*
Shoes	7,993	8,309
Hose	5,575	3,964
Profile	5,032*	3,332*
Floor tile	-	-
Sheet & Film	8,218*	7,787*
Total	**66,258**	**56,311**

*estimated volume of market share by the owners.

For comparison of estimated volume of market share by the owner's regarding the quantity, the amounts of selected PVC recycled product in 2015 and 2016 are plotted and combined with the previous results in 2013 and 2014 that were calculated based on the assumption used in the previous phases as shown in Figure 4.14. In Figure 4.14, the PVC wastes in 2013 and 2014 are covered by 7 products, pipe & fitting, profile, cable, floor tile, floor covering, shoes, and hose. The PVC wastes in 2015 and 2016 cover eight products including addition of sheet & film product.

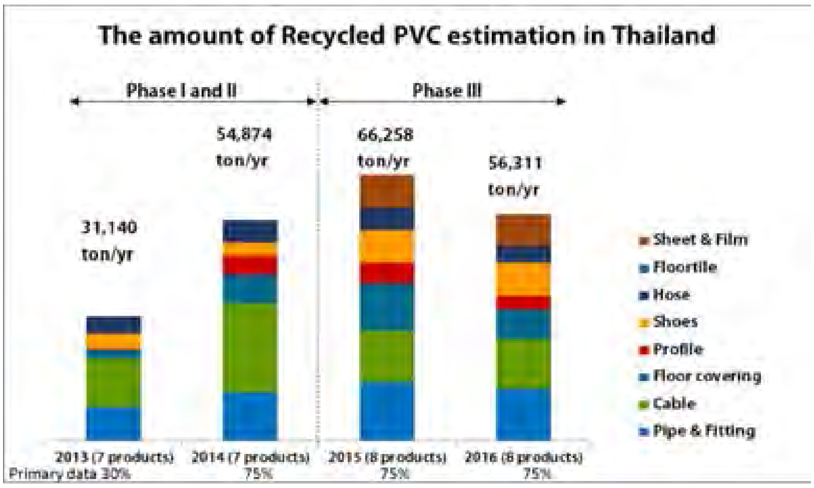

Figure 4.14 The amount of recycled PVC products in 2013 and 2016 in Thailand (7 target products (2013 and 2014) and 8 target products (2015 and 2016)).

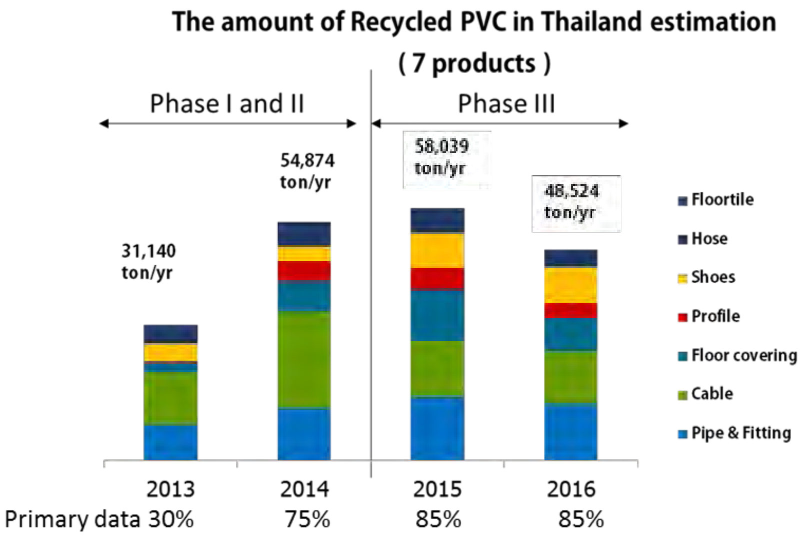

Figure 4.15 The amount of recycled PVC products in 2013 and 2016 in Thailand cover seven products.

In comparison of seven products from 2015 to 2016, the data was estimated from additional percentages of primary data compared with our previous study (Figure 4.15). The amount of PVC recycled wastes was significantly decreased by 15 % from 2015 to 2016 (Figure 4.14). The major reason of the waste reduction could be due to the decrease in PVC resin price from downturn of oil price, as a result the converters prefer to use the PVC resin driving to a lower recycling compound ratio. Another reason is that the PVC products in Thailand cannot compete with China's price, which is cheaper than local production price, therefore it is effect to the overall PVC circulation. The trend of PVC recycled in 2015 was slightly grew by 5.5% based on 7 products compared with 2014 (Figure 4.15). The increment was lower than the expectation since in the study (phase 3) had more additional visited sites than the previous phases. However, from surveys, In order to adjust the accuracy of credible result, we eliminated the overlap data among the recyclers which come from the share products in their businesses as shown in Figure 4.16

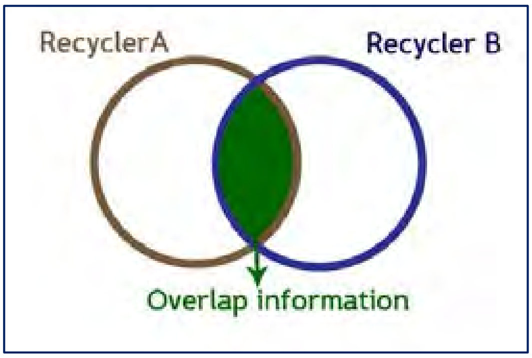

Figure 4.16 Overlap information between recycler A and B.

4.3 Off-spec Products Estimation

Industrial wastes, which include all of wastes are sent out from factories, report by Thailand Department of Industrial Works (DIW, 2015) were used to determine the off-spec products of eight PVC product used as an input data sat for MFA model to eliminate off-spec products before calculating in further steps. Table 4.5 shows the off-spec products estimation outcome.

Table 4.5 Off-spec products estimation outcome

Products	Off-spec products reported in 2015	PVC products production in 2015 from MFA model	Input to MFA model
Sheet & film	32,358.78	269,251.85	12%
Cable	14,354.00	131,690.00	11%
Profile	3,426.00	52,707.20	7%
Pipe & fitting	10,740.00	206,548.00	5%
Shoes	1,400.00	29,034.00	5%
Hose	337.50	8,655.00	4%
Floor tile	120.00	13,079.00	1%
Floor covering	-	113,227.00	0%

Sheet & Film had the highest amount off-spec product generated during production. The reason of this could be that sheet & film had a high producing portion in Thailand (AVC, 2013) comparing to others and the off-spec was generated due to changing production line, for instance, changing pattern and thickness in calendaring process. The second highest amount of off-spec product was a cable. The production process of cable is extrusion, it also generates wastes during changing production line (e.g., changing color of the product). In addition, the production of sheet & film and cable are small scale production. They hardly control their qualities that is the reason why many off-spec products are reported. Pipe and hose are produced by extrusion as same as a cable but their produced in medium to big scales. Thus it could be easier to control the quality. Pipe production in Thailand is controlled stringently and separated color and size by machines. For profile, shoes and fitting, they are produced by injection which is easy to control the quality and change their production line. Another product is floor tile which is added many strength additives and other raw materials to make it strength to use, with high price of raw material and additive costs. Thus their production process must be minimize off-spec portion. For floor covering, all converters claimed that the floor covering are recycled in the factories for production by 100%. Noted that this amount still not enough for production and need to buy in large volume from other. Thus, no records of off-spec floor covering as an industrial wastes because they can use it to be a raw material of production.

To conclude, the factors relevant to off-spec products cooled be due to size of each target product, quality control, domestic consumption and process.

4.4 Material Flow Analysis Model Results

The material flow analysis of martial or waste inflow and outflow of all eight targeted PVC products are presented in Figures 4.17 and 4.18. This calculation include the domestic PVC production between 1971 and 2016 as an input. The result shows that approximately 200,000 to 330,000 tons/year of post-consumer PVC wastes would be generated from years 2013 to 2016. By adjusting assumption in the MFA model with the combination of GDP and normal distributions. After 2016 calculated by normal distribution, it is immediately apparent that the estimated out flow showed a fluctuate trend (Figure 4.17). A similar trend was observed in an actual inflow data. Comparing with Figure 4.18 where the outflow (was calculated based on only normal distribution) shows that approximately 100,000 to 150,000 tons/year of post-consumer PVC wastes would be generated from years 2013 to 2016. From the results of different distributions patterns, it can be seen that the outcome which including the GDP distribution had a higher outcome for two times. In addition, the waste outflow pattern (Figure 4.18) present a smooth trend and did not fluctuate compare with the actual inflow data. All in all, the result which includes the GDP distribution seem to be more reliable than the result predicted by the normal distribution.

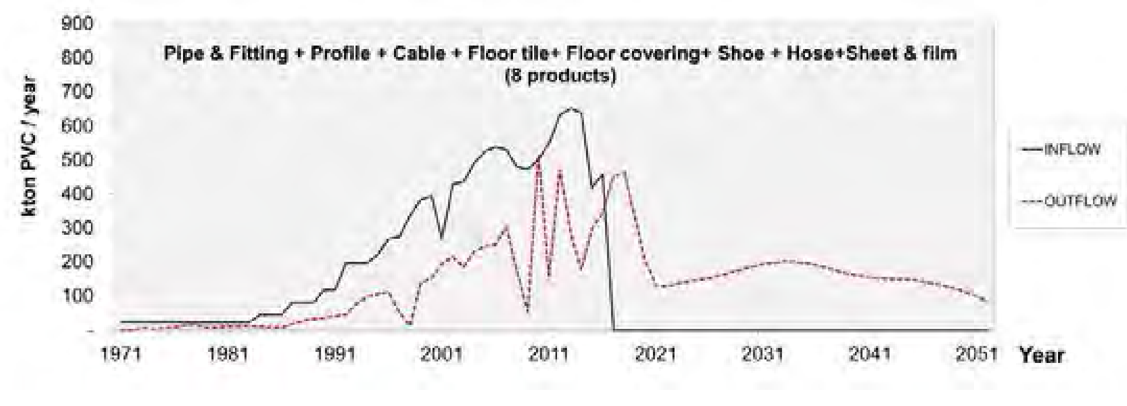

Figure 4 .17 Inflow and outflow of all target PVC products (Calculated based on normal and GDP distributions).

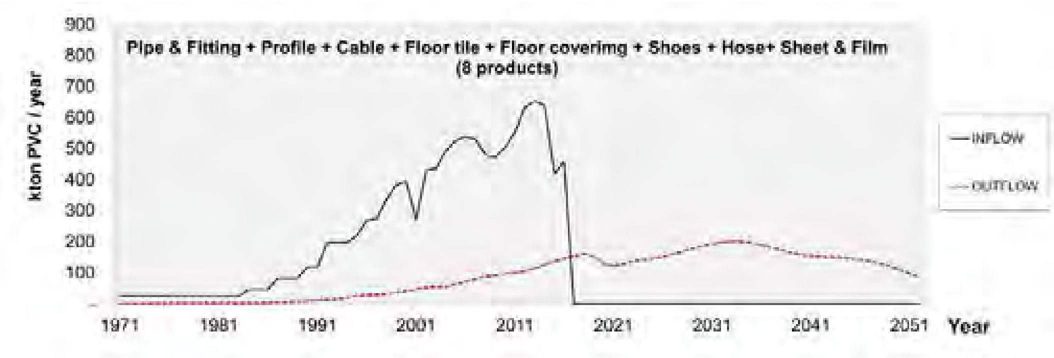

Figure 4 .18 Inflow and outflow of all target PVC products (Calculated based on only normal distribution).

4.5 Recycle Amount Compare to MFA Model Result

In order to get an overview of the recycling situation of PVC products in Thailand, the MFA model, calculated based on normal and GDP distributions, was applied to calculate the outflow, which is the total annual PVC wastes. The data obtained from the model is compared with the total recycled amount obtained from the estimated data from the site visit and interviews by phone & email as shown in Table 4.6

Table 4.6 Recycle amount in 2015 and 2016 compare to outflow from MFA model

Products	2015			2016		
	Outflow from MFA model (ton)	Recycle amount estimation (ton)	Recycled percent (%)	Outflow from MFA model (ton)	Recycled amount estimation (ton)	Recycled percent (%)
Pipe & Fitting	10,461	14,676	140	11,820	13,106	111
Hose	6,151	5,575	91	7,201	3,964	55
Floor covering	25,144	11,712	47	29,437	7,493	25
Cable	31,820	13,051	41	35,079	12,321	35
Shoes	20,417	7,993	39	23,903	8,309	35
Profile	17,990	5,032	28	19,833	3,332	17
Sheet & Film	175,391	8,218	5	205,334	7,787	4
Floor tile	10,251	0	0	9,753	0	0

From table 4.3, the outflow from MFA model (ton) was calculated based on all PVC wastes in this study from post-consumer wastes but the recycled amount estimation (ton) is a part of PVC wastes, which was collected to recycle shops. Therefore, we can calculate amount of recycled of each PVC product. Overall, the results show that pipe & fitting had the highest percentages of recycled and the amount of recycled dropped moderately from years 2015 to 2016.

4.5.1 Pipe and Fitting

There are four recycle shops involved pipe & fitting production as a main product. There are applications which have a long service life therefore the amount of PVC pipe & fitting wastes, generated from the MFA model during 2015 and 2016 were 10,461 and 13,106 tons respectively. However, the recycled PVC pipe and fitting in Thailand were 14,676 tons in 2015 and 13,106, in 2016, which were higher than the outflow from MFA estimation. There are several explanations for this difference as follows:

- Average service lifetime and lifetime span of PVC pipe and fitting used in the MFA model may a few differences from the real situation
- Different usages of pipe & fitting can cause a variation in service lifetimes e.g., the lifetimes maybe vary 2-3 years compared when the service lifetime reported by manufactures (20-30 years).
- Premature service use of pipe and fitting such as early replacement, accidental damage, poor construction planning, etc.

4.5.2 Hose

PVC hose the second highest recycled product by 91 % in 2015 and 55% in 2016. It might be possible that nowadays people know that this product can sell to recycle shops after using. Moreover, the price of discarded hose which consumers can get was reasonable.

4.5.3 Floor Covering

In this study, floor covering was found in a large portion at K’Neung recycle shop who is the major recycle shop player of this product. From the investigation, we can be conclude that the floor covering had high demand in recycle market because the converters, who are mainly producers if floor covering, demand to use it as a part of recycled compound. The reason of this is that the floor covering production has low price and also contain plasticizers from primary production so it can reduce production cost in economy of huge scale. Furthermore, there are a wide ranges of quality, some grades can be produced from 100% recycled compounds. In downturn of the floor covering business and lower prices of PVC resin directly caused the reduction of recycling portion by 22% from 2015 to 2016.

4.5.4 Cable

The recycling portion of this product seem not different between 2015 and 2016 since the major recycle shop had similar ordering in 2015 and 2016. Thus, they bought cables from consumers around the quantity that was ordered because of limited space in shop.

4.5.5 Shoes

The recycling ratio of shoes look not change to between 2015 and 2016. Shoes had general recycling portion. The type of shoes was recycled was boot shoes and they not well known that it can recycle. Now the recycle shops buy it from collectors.

4.5.6 Profile

In the case of profile which had one major recycle shop. They had lower ordering from converters in 2016 so they bought it in lower portion. Thus, the results were indicated that the recycling percent reduced for 10 % from 2015 to 2016.

4.5.7 Sheet and Film

Sheet & film product just had studied only in phase III. We found only two major recyclers that treaded sheet & film because it was hard to collect and separate type of plastics after discarded. Today, Vinyl sheet is the product that people well- know it is PVC sheet and can sell it to recyclers as shown in Figure 4.18

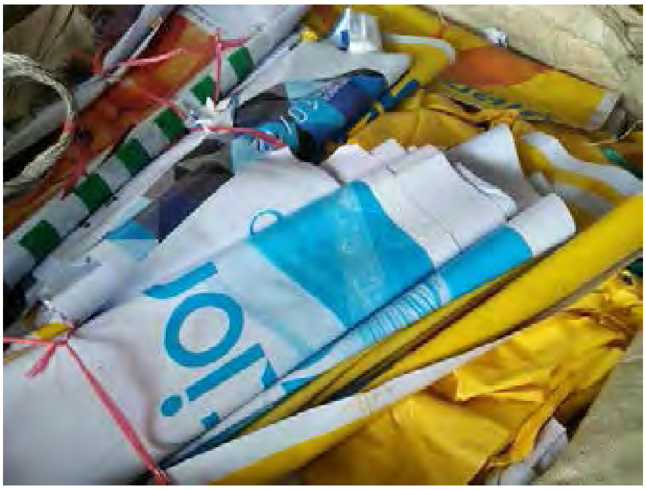

Figure 4.19 Vinyl sheets at recycle shop.

4.5.8 Floor Tile

In the case of PVC floor tile waste, the amount of PVC waste from floor tile is not many as PVC pipe, profile, or cable. This is a visited special case for this study because unlike other PVC products, it was not found at any recycle shop but was found in most of the visited construction dump sites in phase 2 study. It is believed that many visited glues and concrete contaminates floor tile that make PVC floor tile waste not appropriate for recycling.

4.6 Off-spec Products Sensitivity Analysis

The normal plastic defects or off-spec products percent in routine manufacturing process is about 2.5% to 5% (Tuammee, 2007) because now the manufactures do not want to waste money on defects. However, the off-spec products can be occurred over the normal range in some applications Sheet & Film, Profile and Cable from the results, section 4.3. In order to find out that the off-spec products results was an effect to MFA model results or not, the off-spec products sensitivity analysis has been done by assuming percent off-spec products of Sheet & Film, Profile and Cable with 3.75% (from the average of plastic defects in manufacturing process). The results before and after adjusting off-spec products percent are shown in Table 4.7 and Figure 4.20.

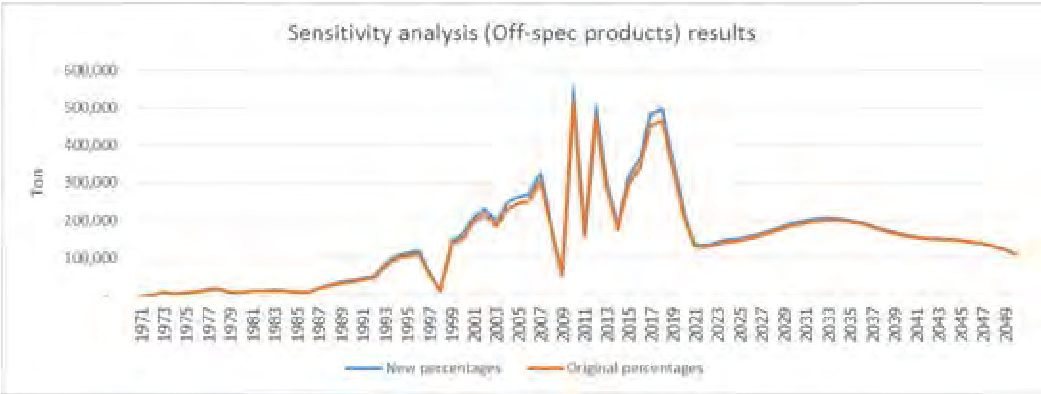

Figure 4.20 The results from MFA model before and after changing off-spec products percentages.

Table 4.7 The results from MFA model before and after changing off-spec product percentages compare to recycle amount in 2015 and 2016

2015						
Products	Original percentages off-spec products			New percentages off-spec products		
	Outflow from MFA model (ton)	Recycle amount estimation (ton)	Recycled percent (%)	Outflow from MFA model (ton)	Recycled amount estimation (ton)	Recycled percent (%)
Cable	31,820	13,051	41.02	34,412	13,051	37.93
Profile	17,990	5,032	27.97	18,618	5,032	27.03
Sheet & Film	175,391	8,218	4.69	191,834	8,218	4.28
2016						
Products	Original percentages off-spec products			New percentages off-spec products		
	Outflow from MFA model (ton)	Recycle amount estimation (ton)	Recycled percent (%)	Outflow from MFA model (ton)	Recycled amount estimation (ton)	Recycled percent (%)
Cable	35,079	12,321	35.12	37,937	12,321	32.48
Profile	19,833	3,332	16.80	20,525	3,332	16.23
Sheet & Film	205,334	7,787	3.79	224,584	7,787	3.47

The results from the MFA model after adjusting the off-spec product percentages indicated the similar trend as the results, in section 4.4 which is the outflow from MFA model (calculated based on normal and GDP distributions). The result after adjusting off-spec percent of Sheet & Film, Profile and Cable with 3.75%, higher than before adjusting by 6% (Figure 4.20). Furthermore, when compare to recycle amount in 2015 and 2016 the recycled percent change around 0.32 to 3.00% which are insignificant changes (Table 4.7).

Overall, it can be concluded that adjusting off-spec products percentage sent insignificant changes to the recycled percent of each product.

CHAPER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

To conclude, this work focuses on the developing of material flow analysis (MFA) model for target PVC products and their wastes in Thailand which consists of pipe & fitting, cable, profile, flooring, calendaring, footwear, hose and sheet & film. The MFA model was successfully developed and used to estimate the amount of target PVC wastes. The amount of target PVC product data from 1971 to 2016, the average service lifetime of the product and GDP and normal distributions were included for the waste prediction model. The MFA results revealed that the PVC wastes accumulation in Thailand rose continuously each year due to the increase in domestic consumption and production without recycling process. The fluctuated trend was observed which is similar to the pattern that obtained from the primary data after adjusting distribution to the combination of GDP and normal distributions. The Off-spec products were taken into the account as an inflow data in the MFA model for better estimation on the post-consumer product. Sizes of the product, domestic consumption, processes are main factors affecting a number of off-spec products being generated. The recycled PVC wastes increased steadily from 2013 to 2015 regarding primary information and expansion on recycling businesses. After that, there was a decline in 2016 because of the downturn in oil price and lower (floor covering) in domestic consumption. Some of the PVC products such as pipe & fitting have high recycled rate whereas some of the products still have a low recycling rate. It can be concluded that the recycle option plays a significant role in achieving sustainable management of PVC wastes. The findings from this study could be used to support Thai government making policies regarding PVC waste management which can tackle the problem precisely for sustainable management of PVC plastics in future.

5.2 Recommendations

Although the Material Flow Analysis (MFA) was successfully conducted for PVC products and wastes in Thailand, several recommendations are proposed as follows:

5.2.1 Recommendations for Improvement of An Accuracy of MFA Model

The materials flow for the PVC product metabolism should include the consumption of the product. This is because the product being produced, might not be only are representative to be totally consumed in the use phase. In the case of using production as an input, it would be better if we can use the actual data from the manufactures of the target products in order to validate the accuracy of model. For the average service lifetime and service lifetime distribution of PVC products, they should be obtained from primary data in a long period of time. The sensitivity analysis of off-spec products should be done in depth on details. The factors which sent effects on the result from MFA model and the amount of PVC recycled in Thailand, for instance, distributive patterns, average service lifetime ,domestic consumption, the number of recyclers and converters should be taken into consideration.

5.2.2 Recommendations for Using MFA Model to Predict the Other Plastic Wastes in the Future

The MFA model can be applied for other plastic products, it could help the government agencies to establish and launch suitable campaigns for tackling waste problems in Thailand.

REFERENCES

Asean Vinyl Council. (2013) PVC Information Report for Research. Thailand: AVC.

Brunner, P.H., and Rechberger, H. (2000) Practical Handbook of Material Flow Analysis. Florida: Lewis Publishers.

Choonhajutha, N. (2010) South East Asia PVC Review and Outlook. Thailand: AVC.

Hendriks, C., Obernosterer, R., Muller, D., Kytzia, S., Baccini, P., and Brunner, P.H. (2000) Material Flow Analysis: A tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. Local Environment, 5(3), 311-328.

Kahhat, R. and Williams, E. (2012) Materials flow analysis of e-waste: Domestic flows and exports of used computers from the United States. Resources, Conservation and Recycling, 67, 67-74.

Kleijn, R., Huele, R., and Voet, E. (2000) Dynamic substance flow analysis: The delaying mechanism of stocks, with the case of PVC in Sweden. Ecological Economics, 32, 241-254.

Leadbitter, J. (2002) PVC and sustainability. Prog. Polym. Sci., 27, 2197–2226.

Mersiowsky, I. (2002) Long-term fate of PVC products and their additives in landfills. Progress in Polymer Science, 27, 2227–2277.

Mutha, N.H., Patel, M. and Premnath, V. (2006) Plastics materials flow analysis for India. Resources Conservation and Recycling, 47, 222-244.

Nakem, S., Malakul, P. and Nithitanakul, M. (2016) Material flow analysis (MFA) and life cycle assessment (LCA) study for sustainable management of PVC wastes in Thailand. Paper presented at The 26th European Symposium on Computer Aided Process Engineering (ESCAPE26), Portoroz, Slovenia.

National Metal and Materials Technology Center. (2012) Sustainable Production and Consumption of PVC Products. Thailand: MTEC

Park, J., Hong, S.J., Kim, I., Lee, J.L., and Hur, T. (2011) Dynamic material flow analysis of steel resources in Korea. Conservation and Recycling, 55, 456-462.

Patel, M.K., Jochem, E., Radgen, P., and Worrell, E. (1998) Plastics streams in Germany—an analysis of production, consumption and waste generation. Conservation and Recycling, 24, 191-215.

Petroleum Institute of Thailand (2017) PTIT Focus: Statistics Petroleum and Petrochemical. Thailand: Priewish.

Rodcharoen, T. (2013) Life cycle material flow analysis of PVC products in Thailand. M.S. Thesis, The Petroleum and Petrochemical College, Chulalongkorn University, Bangkok, Thailand.

Sadat-Shojai M., Bakhshandeh G.R., (2011) Recycling of PVC wastes. Polymer Degradation and Stability, 96, 404-415.

Tuammee, S. (2007). Defect reduction in plastic process by applying the design of experiments a company case study in plastic industry B.Eng. Thesis. Industrial Engineering, King Mongkut's University of Technology North, Bangkok, Thailand.

Yarahmadi, N., Jakubowicz, I. and Martinsson, L. (2003) PVC floorings as post-consumer products for mechanical recycling and energy recovery. Polymer Degradation and Stability, 79, 439–448.

Zhou, Y., Yang, N., and Hu, S. (2013) Industrial metabolism of PVC in China: A dynamic material flow analysis. Resources, Conservation and Recycling, 73, 33-40.

Murphy, M.A. “PVC Disposal and Recycling.” 18 April 2015 <http://greenliving. nationalgeographic.com/pvc-disposal-recycling-20124.html.>

Haohua East China Chemical Corporation. “The introduction of PVC.” 19 June 2016. < http://www.hhhd.chemchina.com>

Taneja, G.S., (2008) “Consumer behavior.” 12 February 2016. < http://economicsmicro.blogspot.com>

World Bank. “Gross Domestic Product.” 20 June 2016. <http://www.investopedia.com/terms/g/gdp.asp>

APPENDICES

Appendix A Input Data of Material Flow Analysis (MFA) Model

Table A1 Domestic PVC resin consumption

Year	Domestic Consumption (ton)
1971	20,000
1972	20,000
1973	20,000
1974	20,000
1975	20,000
1976	20,000
1977	18,840
1978	18,840
1979	18,840
1980	18,840
1981	18,840
1982	18,840
1983	18,840
1984	37,680
1985	37,680
1986	37,680
1987	65,940
1988	65,940
1989	65,940
1990	94,200
1991	94,200
1992	157,785
1993	157,785
1994	157,785
1995	176,625
1996	214,305
1997	219,015
1998	268,470

Table A1 (cont.) Domestic PVC resin consumption

Year	Domestic Consumption (ton)
1999	306,150
2000	315,570
2001	215,000
2002	343,000
2003	349,000
2004	393,000
2005	420,000
2006	431,000
2007	424,000
2008	384,000
2009	377,000
2010	401,000
2011	440,145
2012	504,931
2013	521,797
2014	510,729
2015	523,303
2016	573,164

Appendix B Output Data of Material Flow Analysis (MFA) Model

Table B1 Outflow of MFA model (Calculated based on normal distribution)

Year	Out flow of PVC wastes (ton)	Year	Out flow of PVC wastes (ton)
1971	0	2012	105,356
1972	96	2013	114,142
1973	732	2014	125,525
1974	1,938	2015	137,287
1975	2,574	2016	146,361
1976	2,670	2017	153,966
1977	2,688	2018	161,018
1978	2,800	2019	154,744
1979	2,987	2020	130,956
1980	3,035	2021	121,871
1981	3,032	2022	128,065
1982	3,050	2023	136,974
1983	3,095	2024	143,359
1984	3,171	2025	146,462
1985	3,389	2026	152,263
1986	4,201	2027	160,594
1987	5,651	2028	169,586
1988	6,805	2029	178,261
1989	8,306	2030	186,427
1990	10,603	2031	193,449
1991	12,359	2032	198,648
1992	14,193	2033	201,128
1993	16,858	2034	200,430
1994	20,414	2035	196,537
1995	25,068	2036	189,918
1996	27,691	2037	181,774

Table B1 (Cont.) Outflow of MFA model (Calculated based on normal distribution)

Year	Out flow of PVC wastes (ton)	Year	Out flow of PVC wastes (ton)
1997	29,301	2038	173,088
1998	32,420	2039	165,420
1999	36,736	2040	159,348
2000	41,529	2041	155,087
2001	47,462	2042	152,348
2002	52,669	2043	150,448
2003	54,186	2044	148,673
2004	55,351	2045	146,282
2005	63,365	2046	142,579
2006	72,527	2047	137,041
2007	80,816	2048	129,919
2008	87,740	2049	120,823
2009	92,847	2050	109,991
2010	96,986	2051	97,905
2011	100,081	2052	85,094

Table B2 Outflow of MFA model (Calculated based on GDP and normal distributions)

Year	Out flow of PVC wastes (ton)	Year	Out flow of PVC wastes (ton)
1971	0	2012	471,910
1972	1,686	2013	286,514
1973	7,379	2014	173,655
1974	4,742	2015	297,626
1975	6,879	2016	342,359
1976	10,008	2017	450,083
1977	15,937	2018	463,912
1978	16,989	2019	334,785
1979	7,808	2020	199,274
1980	8,622	2021	129,017
1981	12,441	2022	125,753
1982	13,035	2023	134,536
1983	13,221	2024	140,803
1984	11,861	2025	143,800
1985	9,044	2026	149,504
1986	9,153	2027	157,758
1987	18,642	2028	166,680
1988	27,827	2029	175,297
1989	34,012	2030	183,427
1990	36,888	2031	190,445
1991	42,138	2032	195,691
1992	47,466	2033	198,291
1993	78,318	2034	197,796
1994	97,867	2035	194,187
1995	105,632	2036	187,918
1996	110,732	2037	180,158

Table B2 (Cont.) Outflow of MFA model (Calculated based on GDP and normal distributions)

Year	Out flow of PVC wastes (ton)	Year	Out flow of PVC wastes (ton)
1997	54,694	2038	171,855
1998	12,612	2039	164,534
1999	137,688	2040	158,751
2000	152,382	2041	154,710
2001	195,065	2042	152,125
2002	216,023	2043	150,326
2003	184,649	2044	148,611
2004	230,440	2045	146,253
2005	244,694	2046	142,566
2006	251,297	2047	137,041
2007	304,226	2048	129,919
2008	171,082	2049	120,823
2009	52,388	2050	109,991
2010	515,715	2051	97,905
2011	157,999	2052	85,094

Appendix C List of Companies and Date to Visit

Table C1 List of recycle shops

Company	Products	Date of Visit
Corporation (K'Neung)	Floor covering*, Hose and Sheet & Film	7/9/2016
Nimcraft	Floor covering, Profile and Sheet & Film	15/9/2016
888Lion	Cable* and Shoes	16/9/2016
Aor. Chareonsub	Pipe & Fitting, Cable, Floor covering, Shoes and hose	16/9/2016
Sa-ne PVC	Pipe & Fitting*	16/9/2016
Nan Hospital	Medical Products*	8/10/2016
HV plus	Pipe & Fitting, Cable, Floor covering, Shoes and Hose	16/11/2016
Dura-inter	Profile*, Hose and Floor covering	16/12/2016
BR recycle	Many plastic types	11/12/22016
Yingchareonsub PVC	Pipe & Fitting, Cable, Floor covering, Shoes, Profile and Hose	Contact by phone&email conver-sation
LSA plastic	Pipe & Fitting, Cable and Shoes	Contact by phone&email conver-sation
Corporation (K'Foo)	Sheet & Film* and Shoes	Contact by phone&email conver-sation
Corporation (K'Thongsook)	Hose and Sheet & Film	Contact by phone&email conver-sation

Table C1 (cont.) List of recycle shops

Company	Products	Date of Visit
Corporation (K'Krit)	Shoes, Hose, Cable and Floor covering	Contact by phone&email conversation
Corporation (K'Komsak)	Sheet & Film* and Shoes	Contact by phone&email conversation
Corporation (Changzoon)	Artificial leather*	Contact by phone&email conversation
Corporation (Chi)	Artificial leather*	Contact by phone&email conversation
Corporation (Su-wan)	Artificial leather and Sheet&Film	Contact by phone&email conversation

* represents the main recyclate in their business

Table C2 List of converters

Company	Products	Date of Visit
MPI	Floor covering converter and Calendaring business	15/9/2559
TPI	Floor covering converter	15/9/2559
Hv plus	Floor covering converter and Sheet & Film producer	16/11/2559
KHI	Floor covering converter and Sheet & Film producer	6/12/2559

Appendix D Actual Data and Estimated of PVC Recycled Products

Table D1 The amount of recycled PVC products in 2015 and 2016

Applications	2015		2016	
	Actual data (ton)	Estimated data (ton)	Actual data (ton)	Estimated data (ton)
Pipe & Fitting	14,676	14,676	13,106	13,106
Floor covering	11,712	11,712	7,493	7,493
Cable	6,525	13,051*	6,161	12,321*
Shoes	7,993	7,993	8,309	8,309
Hose	5,575	5,575	3,964	3,964
Profile	2,516	5,032*	1,666	3,332*
Floor tile		-		-
Sheet & Film	1643.6	8,218*	1557.4	7,787*
Total	**50,642**	**66,258**	**42,255**	**56,311**

* extrapolated basing from owner's estimate of market share

CIRRICULUM VITAE

Name: Ms. Wikanda Khomchu

Date of Birth: September 23, 1992

Nationality: Thai

University Education:

2011-2015 Bachelor Degree of Engineering (Petrochemical and Polymeric material), Faculty of Engineering and Industrial Technology, Silpakorn University, Nakhon Pathom, Thailand

Working Experience:

March-May 2014	Position:	Student Trainee
	Company name:	PTT Global Chemical Public Company Limited

Proceedings:

1. Khomchu, W., Malakul, P., Nithitanakul, M. and Charoensang, A. (23 May 2017) Material flow analysis (MFA) study of PVC wastes in Thailand (phase III). Proceedings of the 8th Research Symposium on Petroleum, Petrochemicals, and Advanced Materials and the 23th PPC Symposium on Petroleum, Petrochemicals, and Polymers, Bangkok, Thailand.
2. Khomchu, W., Malakul,P., Nithitanakul, M. and Charoensang, A. (2017) Material flow analysis (MFA) study for sustainable management of PVC wastes in Thailand. Proceeding of the 27th European Symposium on Computer Aided Process Engineering (ESCAPE 27), Barcelona, Spain.