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THESIS

LIFE CYCLE ASSESSMENT OF PAINTS FOR REFRIGERATOR IN THAILAND

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the Requirements for the Degree of
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In this research, environmental impacts in the life cycle of paints including polyester TGIC powder coating, polyester-epoxy powder coating, and solvent-based paints which used for refrigerator in Thailand were evaluated by using life cycle assessment technique. SimaPro 5.1 with Eco-Indicator 95 method was used to quantify environmental impacts. The system boundary was included the production of raw materials, the production of paint, the coating paint on workpiece, use, disposal, and the entire transportation (including transportation in raw materials, paint, workpiece coated by paint, and wastes from production processes). The inventory data used in this research were collected from Nippon Paint and Jotun Powder Coating Company which have major market share of paint production industries in Thailand. From results, the significant impact categories in the paint production were summer smog, acidification, and carcinogens. Water consumption in the coating phase was a major factor that mostly contributed to the life cycle environmental impacts of paint. To improve environmental impacts, the use of paper filler booth instead of recirculating water wall paint booth and the installation of water-saving devices were proposed. The environmental life cycle impact of polyester powder coating, polyester-epoxy powder coating, and solvent-based paints were reduced by approximate 36-39%. In case of paint used the utility database of SimaPro, the electricity consumption and emission during coating process in the coating phase was a major factor that mostly contributed to the life cycle environmental impacts of paint. Acidification and heavy metals were significant impact categories for paint production calculated using the utility database of SimaPro.

Krisakorn Jeamjumrussin — Student's signature

[signature] — Thesis Advisor's signature

4 / May / 2006

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Krisakorn Jeamjumrussin

January 2006

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LIFE CYCLE ASSESSMENT OF PAINTS FOR REFRIGERATOR IN THAILAND

INTRODUCTION

At present, life cycle assessment (LCA) becomes a significant role due to many factors concerning environmental problems such as greenhouse effect, acidification, ozone layer depletion, etc. Furthermore, the non-tariff barriers (NTB) related to environmental problems have been imposed by environmental concerning countries and also developed countries around the world. The examples of NTB are the “Integrated Product Policy (IPP)”, the “Wastes from Electrical and Electronic Equipment (WEEE)”, and the “Restriction of use of certain Hazardous Substances in Electrical and Electronic Equipment (RoHS)”. Manufacturers worldwide including Thailand have been forced either directly or indirectly by this situation.

Life cycle assessment is a framework and methodology for the identification of environmental friendly products or processes. It is widely used for environmental assessing, comparing environmental impact, and designing of more environmental friendly products or processes. Performing LCA, a technique for assessing the environmental performance of a product, process or activity from ‘‘cradle to grave”, the database is necessary to build up. At present, there are plenty of LCA softwares such as SimaPro 5.1, Gabi, Umberto, etc., which some database has already existed. In Thailand, most of LCA studies have been done using software to assess environmental impact because it is convenient and easy to apply. However, an error caused by using the database from foreign countries is certainly existed. Because of this reason, it is necessary to build Thailand’s own database. Recently, some database, which has been already studied and collected, is shown in Table 1.

Table 1 Current status of LCA database in Thailand

Type	Detail of collection	Degree of completeness *	Organization
Petroleum	Diesel, crude oil, naphtha, heavy oil (low S), heavy oil (high S)	1	TEI (with JEMAI)
Electric power	Grid mix	3	TEI, KU, KMUTT
Gas	NG, LPG	1	TEI
Mining	Coal	2	Energy Research Institute (ERI)
Iron and steel	Shape, plate, bars, Zn coated sheet, welded pipes, tin free steel, tin plate, Ni-based stainless	2	TEI, MTEC
Paper	Paper, board	2	Chem. Eng (CU)
Chemical	Petrochemicals (PE, PVC, PS, PET, PP, ABS, and EPS), basic chemicals	0-1	KU, MTEC
Cement	Portland, fly ash	3	TEI, Siam Cement
Non-ferro	Cu wire, Cu tube	2	MTEC
Water	Tab water	2	AIT, KU

Note: * 0 = no data, 1 = a few data, 2 = moderately data, 3 = complete

Source: Piumsomboon and Malakul (2005)

Moreover, the framework and roadmap development have been prepared in order to support the set up of green purchasing networks and services in Thailand (Piumsomboon, P. and P. Malakul., 2005). The primary life cycle fundamental database, which has to collect consists of:

1. Infrastructure: coal, petroleum, electric power, and transportation system, etc.
2. End of life/waste management: recycle, landfill, anaerobic digestion, and incineration
3. Basic materials: plastics, basic chemicals, paper, rubber, paints, etc.

Paints that are basic materials and parts of finishing of the products in various industries such as housing estate, automotives, and electric appliances are essential to be collected as LCA database in Thailand. Paints can be categorized into 3 groups which are solvent-based, water-based, and powder coating paints. In Thailand, the paint production capacity is approximately 330,000 tons per year. Since 1998, use and demand of paints are now increasing every year (The Thai Industrial Standards Institute, 2003). Although paint production in each year is less when comparing to other products but the harmful from the production and use of paint is high. The toxic of paint mostly comes from heavy metals such as lead in pigments and volatile organic compounds emission from solvents.

Electrical and Electronic Industries are the crucial industries in Thailand because of their first exporting level, of the exporting value more than million-million baht (Ministry of Commerce Thailand, 2004). Moreover, they are also the first industries affected by the non-tariff barriers. Therefore, this research was focused on the LCA study of paints used for the refrigerator which is Electrical and Electronic Equipment. The environmental assessment was considered in all steps including raw materials acquisition, production, use, disposal, and transportation. LCA can show the important environmental burdens in various aspects and categories throughout the life cycle of paint from raw materials acquisition through their end-of life. As the result, the modification or optimization could be focused at the appropriate process.

In this research, the environmental impacts of paint including polyester TGIC powder coating, polyester-epoxy powder coating, and solvent-based paints for the refrigerator were investigated by using LCA technique. The scope of this study included raw materials production, transportation, paint production, energy and materials used in each process, coating, and disposal during production process. For LCA data compilation and analysis, SimaPro 5.1 software was used to assess the environmental impacts in various categories including greenhouse effect, ozone layer depletion, acidification, eutrophication, summer smog, heavy metals, carcinogens, energy resources, and solid waste.

Objectives of Research

1. To evaluate and compare the environmental life cycle impact of paints which consists of polyester TGIC powder coating, polyester-epoxy powder coating, and solvent-based paints
2. To propose option for reducing the environmental impacts
3. To develop Thailand database of life cycle of paints which are used for the refrigerator

Scope of Research

The scopes of work were covered:

1. Life cycle inventory (LCI) of polyester TGIC powder coating, polyester-epoxy powder coating, and solvent-based paints, which used for the refrigerator
2. System boundary of the study life cycle of paint covered the production of raw materials, the production of paint, the coating paint on workpiece, use, disposal, and the entire transportation (including transportation in raw materials, paint, workpiece coated by paint, and waste from production processes)
3. The environmental impact assessment using SimaPro 5.1 software with Eco-indicator 95
4. The functional unit as 1 kg of each paints for LCI database and quantity of paint applied to 1 m^2 of workpiece for comparing environmental impact of each paints
5. Suggestion for process modification in order to reduce the environmental impacts

LITERATURE REVIEWS

Life Cycle Assessment (LCA) technique is proper for assessment of the environmental impact because it has emerged production of goods and services throughout the entire life of product cycle. LCA originates from net energy analysis studies, which were first published in the 1970s and considered only energy consumption over the life cycle of a product or process. Some later studies, especially for packaging systems and selecting other consumer products (i.e., diapers) included wastes and emissions (also called Resource and Environmental Profile Analysis), but none of them went further than quantifying materials and energy uses. At this point it was clear that a more sophisticated approach to environmental issues was needed (Azapagic, 1999).

As a result, in 1990 the Society for Environmental Toxicology and Chemistry (SETAC) have initiated activities to define LCA and developed a technical framework (Fava *et al*., 1991) and a code of practice (Consoli *et al*., 1993) for conducting LCA studies. Soon afterwards, the International Organization for Standardization (ISO) stared similar works on developing principles and guidelines on the LCA methodology, resulting in the ISO 14040 series (ISO, 1997). Although SETAC and ISO each other worked independently, a general concept on the LCA framework between the two bodies has been emerged. The ISO standard focuses on the procedures to be followed for conducting LCA with a view to assure transparency, independence and accountability of the LCA processes. SETAC focuses through its various working groups on best practicable methodologies for conducting the different parts of LCA with a view to achieve the use of best scientific insights in conducting LCA (Azapagic, 1999).

<u>Life Cycle Assessment (LCA)</u>

LCA is an environmental auditing tool that quantifies the environmental burdens of an activity including all related systems. Both direct and indirect environmental impacts associated with the product, process or activities are included in the assessment as the concept of "cradle to grave" (SETAC, 1993).

The life cycle of a generic industrial product was defined by SETAC (1991) as being composed of the following stages:

- Raw materials acquisition – all activities necessary to extract raw material and energy inputs from the environment, including the transportation prior to processing
- Processing and manufacturing – activities needed to convert the raw material and energy inputs into the desired product. In practice this stage is often composed of a series of substages with intermediate products being formed along the processing chain.
- Distribution and transportation – shipment of the final product to the end user
- Use, reuse, and maintenance – utilization of the finished product over its service life
- Recycle – begins after the product has served its initial intended function and is subsequently recycled within the same product system (closed-loop recycle) or enters a new product system (open-loop recycle).
- Waste management – begins after the product has served its intended function and is returned to the environment as the waste.

The interactions of these stages with each other and with the external environment are shown in Figure 1. The combined stages constitute the entire cradle-to-grave system.

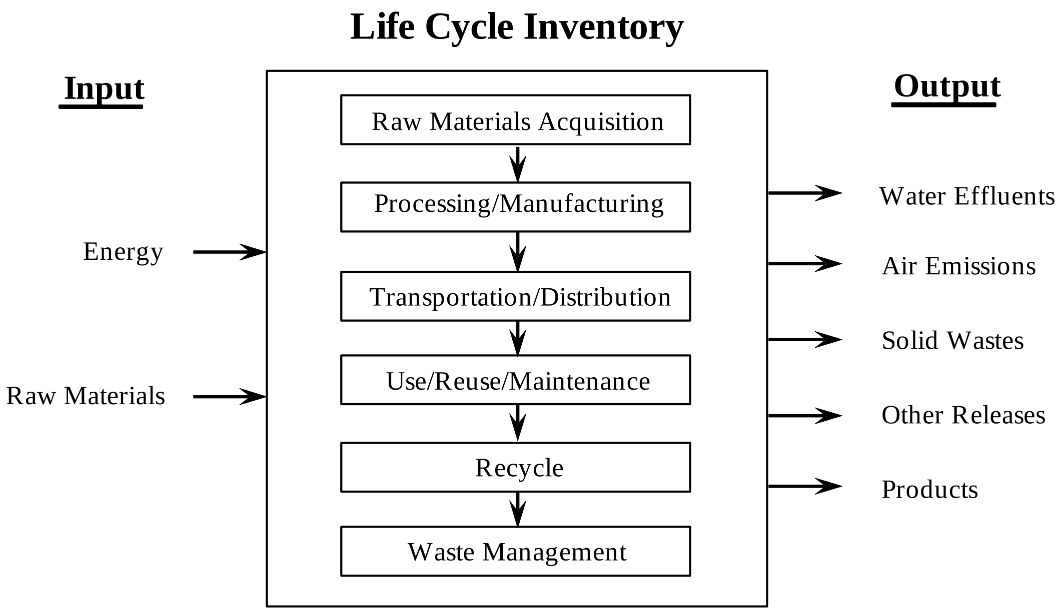


Figure 1 Stages in the life cycle of a product

Source: SETAC (1991)

Truncation of the chain yields partial life cycles which in some cases may be sufficient for the analysis demanded by the study objectives (Todd, 1996). There are three variants of partial LCAs:

- Cradle to gate – analysis upstream of point of truncation
- Gate to grave – analysis downstream of point of truncation
- Gate to gate – analysis between two points of truncation

1. LCA Method

The LCA methodology comprises four stages: goal definition and scope, inventory analysis, impact assessment, and interpretation as illustrated in Figure 2.

- Goal definition and scope - define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.

- Inventory analysis - identify and quantify energy, water and materials usages and environmental releases (e.g., air emissions, solid waste disposal, wastewater discharge).
- Impact assessment - assess the human and ecological effects of energy, water, and material usages and the environmental releases identified in the inventory analysis.
- Interpretation - evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to obtain the results.

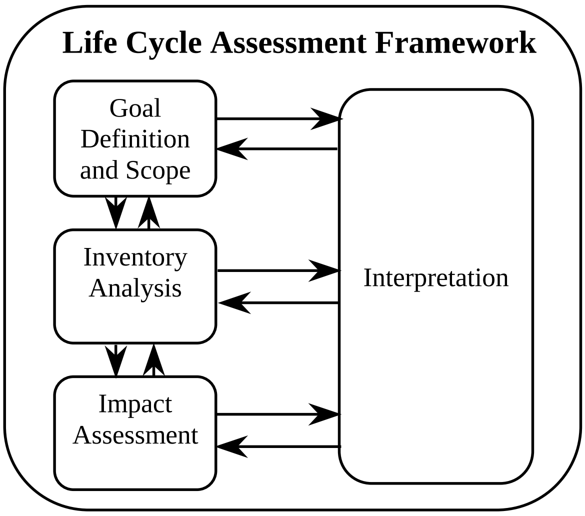


Figure 2 Phases of a LCA

Source: ISO (1997)

2. LCA Application

LCA is one of many environmental management tools (ISO, 1997). It can be used by governments, private sectors, consumer organizations, and environmental groups as a decision support tool (Wenzel *et al*., 1997). The scope of LCA application covered from broad management and policy choices to specific selection of product or process characteristics during design (Ludwig, 1997).

LCA applications (ISO, 1997) can be applied as follows:

- Identification of opportunities to improve the environmental aspects of products at various points in their life cycles
- Decision-making in industry, government, and non-government organizations (NGOs)
- Selection of indicators of environmental performances and measurement procedures
- Marketing, including eco-labelling and improvement of corporate images

Table 2 lists LCA applications based on broad objectives of focus and choice as suggested by Wenzel *et al.*, (1997). Focus refers to a stand-alone diagnostic LCA to identify points of interest within a single life cycle system, whereas choice refers to comparative LCAs of competing alternatives with the ultimate objective of ranking and selection. They also give a more detailed description of the uses of LCA in the private and public sectors as well as NGOs. LCA applications grouped according to users are given in Table 3.

Table 2 LCA applications according to objectives

Objective	Application	Support for decision
Diagnosis	Product development	Background for environmental specifications; design strategies, principles and rules.
	Eco-labelling	Identifies important environmental properties for the product category.
	Community action plans	Identifies environmentally important product groups.
Selection	Product development	On-going identification of the best choices from alternative solutions.
	Cleaner technology	Identifies the best available technology by means of LCA.
	Community action plans	Identifies the best community strategy for a certain problem or product.
	Consumer information	Documents potential environmental impacts of a certain product

Source: Wenzel *et al.* (1997)

Table 3 LCA applications according to user type

LCA user	Application	Example
Government	Community action plans	Incineration versus recycling
		Public transport systems
	Environmentally conscious public purchase	Cars, office supplies
	Consumer information	Eco-labels and Standards
Company	Establish environmental focus	Identification of areas of improvement
		Product-oriented environmental policy
		Environmental management
	Design choices	Concept selection
		Component selection
		Material selection
		Process selection
	Environmental documentation	ISO 14000 certification and Eco-labels

Source: Wenzel *et al.* (1997)

This research uses SimaPro 5.1 with Eco-indicator 95 in the impact assessment step. Detail information are described below.

SimaPro 5.1 Program

SimaPro 5.1 was a software package developed by PRé Consultants B.V., Netherlands. It is the most widely used software for life cycle assessment (LCA) filed. SimaPro 5.1 is successfully used to analyze, improve and manage the environmental performance of products and services by multinationals, consultants, research institutes and universities around the world.

SimaPro 5.1 program includes a large database with a range of data on most commonly used materials (i.e., plastics, metals, etc.) and the most important impact assessment methods (i.e., Eco-indicator 95, Eco-indicator 99, EDIP, etc.) It can immediately start and do not loose time collecting background data. Furthermore, it also ensures that even complex products with complex life cycles are easily compared and analyzed. Results can be calculated with different impact assessment methods; each step is shown and can be fully analyzed (Environmental Expert, 2005).

Eco-Indicator 95

Eco-indicator is a methodology to express the total environmental load of a material or process in a single aggregated score. Although there will never be a perfect method to include all environmental impacts in a generally accepted way but this method is based upon the best available scientific information on environmental damage caused by industrial processes. It is used by many companies worldwide, such as Philips (Environmental Expert, 2005).

This method has kept as close as possible to the methodology of the life cycle assessment (LCA) method as described by SETEC and Centre for Environmental Studies (CML). This is an important starting point because an analysis using the Eco-indicator method is intended to provide the same result as an LCA as far as possible. This starting point means that the method's initial phases are the same as the LCA steps (PRé Consultants, 2002).

The Eco-indicator value is expressed in Eco-indicator points (Pt). In practice the Eco-indicator absolute value is relatively meaningless because the indicator is intended solely for comparative purpose.

Impact categories of Eco-indicator 95 consist of greenhouse effect, ozone layer depletion, acidification, eutrophication, heavy metals, carcinogens, summer smog, winter smog, energy resource, and solid waste. In order to analyze the environmental impacts, the distance to target approach including the damage to human health and ecosystems has been used. The weightings are established by assessing the current and target values for an effect. The greater the distance is the more serious the effect (Goedkoop, 1994).

The calculation structure of Eco-indicator 95 in SimaPro 5.1 consists of characterization, normalization, and weighting (in effect correlation). The structure of the evaluation is shown in Figure 3.

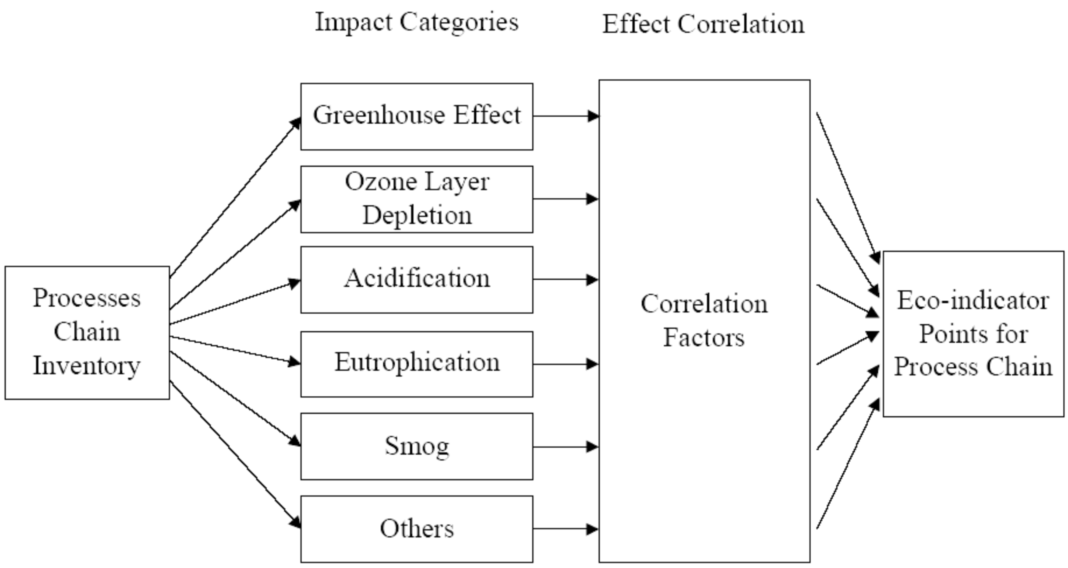


Figure 3 Principle of the Eco-indicator 95

Source: PRé Consultants (1995)

1. Characterization

Characterization is mainly a quantitative step based on scientific analysis of the relevant environmental processes. The characterization has to assign the relative contribution of each input and output to the selected impact categories. The potential contribution of each input and output to the environmental impacts has to be estimated. Characterization can calculate from substances that contribute to an impact categories multiplied by characterization factor. Characterization factor is a factor, which expresses the contribution of a unit environmental intervention (such as the atmospheric emission of 1 kg CFC-11) to the chosen impact categories (such as greenhouse effect and ozone layer depletion). For example, the characterization factor for CO_2 in impact category greenhouse effect can be equal to 1, while the characterization factor of methane can be 21. This means the release of 1 kg methane causes the same amount of greenhouse effect as 21 kg CO_2. The total result is expressed as impact category indicators (characterization result).

2. <u>Normalization</u>

Normalization is used to express impact indicator data in a way that can be compared among impact categories. This procedure normalizes the indicator results by dividing by a selected reference value when reference value is the average yearly environment load in a country or continent per the number of inhabitants.

3. <u>Weighting</u>

In the weighting step, impact category indicator results are multiplied with a weighting factor. These subjective weighting factors are determined according to the distance-to-target principle. The underlying premise is that there is a correlation between the seriousness of an effect and the distance between the current level and the target level. Weighting value can be added to create a total or single score in unit of point (Pt). All factors in this method are shown in Appendix A.

In this research, powder coating and solvent-based paints are the products, which are concerned in the LCA study. Detail information are described below.

Paints

Paints are a material which are applied as liquid or solid to a surface, forms a solid film (paint film) for the purpose of decoration and/or protection. Generally, paint contains binders, solvents, and pigments. Other additives are often presented to give special properties of the paint film. Examples of such additives are rust inhibitors, light stabilizers and softening agents or plasticizers (Schneberger, 1985).

In general, paints are mainly divided into 3 types; solvent-based, water-based, and powder coating paints. The major components of solvent-based paints are solvents, binders, pigments, and additives. Generally, the combination of the binder and solvent is referred to as the paint vehicle. Pigments and additives are dispersed within the vehicle. Traditionally, solvents make up are about 60% of the total composition. Binders, pigments, and additives are approximately 30%, 7-8%, and 2-3%, respectively. A wide variety of solvents are used in solvent-based paints, including aliphatic hydrocarbons, aromatic hydrocarbons (toluene, xylenes, and trimethyl benzenes), ketones (methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK)), alcohols, esters, and glycol ethers.

Water-based paints have water as the solvent to disperse the resin. Usually, they contain up to 80% water and small amounts of other solvents, such as glycol ethers. In the case of powder coating paints, no solvents are used. It consists of binders or resins, pigments, and additives. Therefore, there is not VOCs emission into the atmosphere when powder coating paints are used.

1. Situation of Paints Production in Thailand

At the present, paint and thinner production industries have the total trader more than 200 cases, 90% of total paint and thinner industries are small business which invested by Thai people. Five major companies in this industry including TOA Paint Company (Thailand) Limited, Nippon Paint Company (Thailand) Limited, Srithai Kansai Paint Company Limited, ICI Company (Thailand) Limited and Jotun

Thai Company Limited has 90% of total production capacity. In the case of major companies, they are often share investment to foreign country such as England, Netherlands, Taiwan, Hong Kong, and Japan. All major companies are good quality paint producer and obtain to teach the technique and technology of production from head office in the foreign country except TOA Paint Company (Thailand) Limited which is 100% Thai people producer. List and production capacity of major companies in paint and thinner production industries are shown in Table 4.

Table 4 List of production capacity of major companies in paint and thinner production industries

Producer	Types of paint	Capacity (Ton)
TOA Paint Company (Thailand) Limited	Water-based paints, Solvent-based paints	150,000
Nippon Paint Company (Thailand) Limited	Water-based paints, Solvent-based paints, Powder coating paints	46,000
Srithai Kansai Paint Company Limited	Water-based paints, Solvent-based paints	42,000
ICI Company (Thailand) Limited	Water-based paints, Solvent-based paints	35,500
Jotun Thai Company Limited	Water-based paints, Solvent-based paints	27,500
Others	Water-based paints, Solvent-based paints, Powder coating paints	29,000
Total		330,000

Source: The Thai Industrial Standards Institute (2003)

Type of paint industries could be divided into 2 categories: building paints and industrial paints, of which the proportion of the industrial paints in 2001 was 42.49% of total paints production (The Thai Industrial Standards Institute, 2003).

This research concentrated only paints, which are used for the refrigerator, which are identified as the industrial paints.

2. Industrial Paints Situation in Thailand

Among 30 industrial paint producers, the major producers include Jotun, Nippon Paint, Thai Kansai Paint, Sixma paint, and Chukoku Paint, etc. Paints which are used for the refrigerator industries as part of Electrical and Electronics Industries are solvent-based, water-based, and powder coating paints. Leader for solvent-based paints market, which is used in Electrical and Electronics Industries, is Nippon Paint, which has 36% of market share in 2003. Most of electric appliances needed to use solvent-based paints are refrigerator, compressor, ballast, air condition, washing machine, fan, and rice cooker as the detail shown in Table 5.

Table 5 Quantities of solvent-based paints used in Electrical and Electronics Industry

Type	Market share in 2003 (Million baht)	% Nippon Paint	% Thai DNT Paint	% Thai Kansai Paint	% Thai Paint	% Others
Refrigerator	93	49	28	14	8	1
Washing machine	18	13	-	75	10	2
Rice cooker	11	80	-	-	12	4
Air condition	25	98	-	-	-	2
Compressor	30	31	18	36	-	15 (TOA)
Ballast	29	-	-	-	-	-
Fan	12	-	-	-	-	-
Other	112	-	-	-	-	-
Total	330					

Source: Nippon Paint Company (2003)

In the case of the refrigerator manufacturer in Thailand, the detail of major solvent-based paint customers is shown in Table 6, more than 50% of total values are belong to Kang Yong Electric and Sanyo.

Table 6 List of refrigerator manufacturers who use solvent-based paints

Customer	Million baht
Kang Yong Electric	29
Sanyo	24
Toshiba Consumer	14.5
Thai Toshiba	13
Matsushita	11.5
Others	1
Total	93

Source: Nippon Paint Company (2003)

In the part of powder coating paints, the leader of producing this type paint is Jotun Powder Coating Company, V. Powder Tech, and Nippon Paint Company, which have 30%, 30%, and 20% of market share, respectively. The total production capacity of Jotun Powder Coating Company is 5,000 tons/year, which produced 52% for domestic sale and 48% for export. The total production capacity of Nippon Paint is 1,200 tons/year, which is sold only in domestic.

3. Solvent-Based Paints

There are four major groups of materials which compound together and form paint. They are:

- Pigments

Pigments are naturally occurred or synthetically produced fine powders, which are dispersed or ground into a binding medium and provide the colour and covering power as their major function in paints. Most of the natural pigments are inorganic in nature but a significant number of synthetic pigments are also inorganic. Titanium dioxide (produced from ilmenite ore) is the most important pigment, which is used in paint as it is by far the best white prime pigment available for covering power and exterior weathering performance.

- Binders

Binders, which are commonly called resin or polymer, are usually organic compounds of high molecular weight and each large molecule can contain many repeating parts in its chemical structure. The binder or resin binds the other components (mainly pigments) together into a cohesive, continuous film and provides the adhesive power for a paint to stick to a substrate. In early days most resins or polymers were naturally occurring materials such as vegetable oils, however nowadays most of resins or polymers are synthetically produced and provided specific properties for paints.

- Solvents

The major purpose of solvent use is to reduce (thinning) paints to a suitable handling consistency or viscosity for ease of manufacture and application. After the paint has been applied, the solvent evaporates and leaves the dry paint film on the substrate. These solvents are organic compounds; the major sources are petroleum refining, fermentation of vegetable matter, and chemical synthesis. They are generally divided into two groups; hydrocarbon solvents made up of carbon and hydrogen atoms and oxygenated solvents, which also contain oxygen atoms. Hydrocarbon solvents are further subdivided into two chemical types, aliphatics (e.g. mineral turpentine) and aromatics (e.g. toluene), as well as combinations between both of them.

- Additives

This group of chemicals is comprised of various properties, which are added to paint formulations by paint makers at low levels (usually $<5\%$) to perform specific functions or to improve performance. For example, turps-thinned paints contain drying agents which speed up the drying process. They also contain anti-skinnning agents to prevent the paint forming into a tough skin-like covering in the can. Water thinned paints contain anti-foamers which prevent the roller producing a close knit bubbling effect in the applied paint and thickeners which reduce spattering and also aid the flowablity (Orica Limited, 1992).

3.1 Production process

The raw materials are being handled according to defined recipes. Simply, it can be said that the dry raw materials are being mixed in a base with binders and some solvents (premixing). The next step is dispersion, where the size of the particles is decided. The last step involves let down and colour adjustment. Solvent-based paint production process is shown in Figure 4.

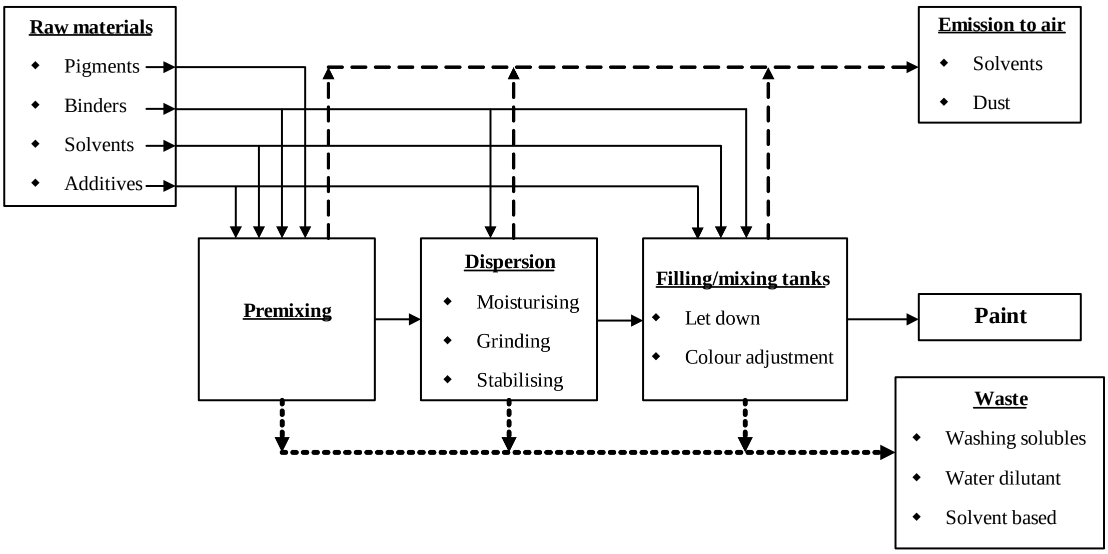


Figure 4 Paint production

Source: Andresen and Voksenopplæringssenter (1999)

3.2 Application method

The many choice of the application method are depends on many factors whether are coated films thickness, paint type used, and so on. The nature of the surface is also important. For example, flat surfaces may require a different method than the contoured ones and also the method of application varies with the nature of the coating substrate, e.g. wood, aluminum, steel, etc. In addition, other factors such as the nature of the films required, the speed and the economy of application demanded, and the curing cycle required are also considered in the selection of a suitable method. Recently ecological aspects and job-safety considerations have also started to play an important role in the selection of application methods. Some of the methods commonly used for the application of paints are as follows: brushing, dip coating, flow coating, spray painting (air spraying and airless spraying), electrodeposition (anodic electrodeposition and cathodic electrodeposition), and etc. (Bengu, 2000).

4. Powder Coating Paints

The powder coating formulation is much like a liquid coating formulation except that most of the components are in solid, melts processable form. The main raw material components that are used in powder coating paints are described below.

- Polymers (sometimes referred to as the binders or resins)

The polymer is the continuous phase or main part of the powder coating paints and is responsible for the integrity of the coating. The polymer can be hard or soft depending on its composition and glass transition temperature. Control of polymer structure allows variation in polymer properties, thus varying coating performance. Different types of polymers that are used in powder coating paints are polyesters, polyurethanes, epoxies, and acrylics. The polymer types are usually separated into thermosets and thermoplastics.

- Pigments

Pigments are used to hide and give color to the substrate. Pigments are generally solid particulate materials. Examples of pigments that are used in coating are titanium dioxide, zinc oxide, iron oxide, carbon black, etc.

- Fillers

Fillers are used to reduce the cost of the coating formulation and/or to improve specific properties such as flow, surface texture, and lubricity. Common fillers are barytes, calcite, mica, talc, whiting, and wollastonite.

- Additives

Additives are the smallest portion of the overall coating, but have the largest impact. Some additives that are used in powder coating paints are included degassing agents, dry flow agents, flow agents, matting agents, texturing agents, rheological additives, and waxes.

4.1 Thermoset powder coatings

Powder coating paints are also divided into thermoset and thermoplastic resins. This research is focused on thermoset powder coatings, which are used in the Electrical and Electronics Industries.

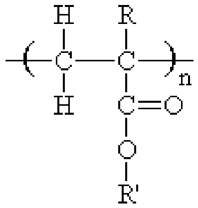
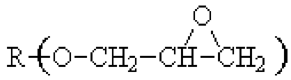
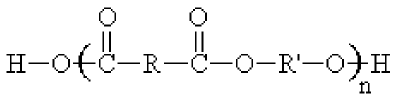
Thermoset resins crosslink to form a permanent film that withstands heat and cannot be remelted. They are used for decorative and protective coatings for architectural structures, on appliances and furniture, and elsewhere. Thermosetting resins are characterized by their excellent adhesion to metal; they are one-coat systems and do not require a primer.

The five basic families of thermoset resins are epoxies, hybrids, polyesters urethane, acrylics and triglycidyl isocyanurate (TGIC) polyesters. The details are described below. Characteristics and structures of all types of resins are shown in Table 7. These five basic families are related to types of powder coating paints as shown in Table 8.

- Epoxies are used for both functional and decorative coatings. Their functional properties include outstanding corrosion resistance and electrical insulation. Decorative epoxies offer attractive finishes that are flexible, tough, and have excellent corrosion resistance and high-impact strength. However, these coatings are lack of ultraviolet resistance and are not recommended for outdoor use. In prolonged exposure to sunlight, they tend to chalk and discolor. Various types of hardeners are used with epoxy powder to optimize its properties.

- Epoxy-polyester hybrid coatings are mainly used for decorative applications. They are more resistant to chalking and over-bake yellowing than pure epoxies, but have a lower surface hardness and are less resistant to solvents. They exhibit better transfer efficiency and a greater degree of penetration into recessed areas of a part than other resins.
- Urethane polyesters are formulated with polyester hydroxyl resin combined with blocked isocyanate hardeners. They exhibit outstanding thin film appearance and toughness as well as good weathering properties.
- Acrylic-urethane coatings are formulated with acrylic resins crosslinked with blocked isocyanates. They have excellent colour, gloss, hardness, weatherability and chemical resistance, and have an excellent thin film appearance. However, they are less flexible than polyesters.
- TGIC polyesters contain a polyester resin crosslinked with TGIC as a curing agent. They offer very good mechanical properties, impact strength and weather resistance. They are resistant to chalking and are often used for outdoor parts, such as patio furniture, lawn mowers, as well as aluminum extrusions and panels for large commercial buildings. In Europe, reduced occupational-exposure limits were recommended for TGIC powders as a result of in vivo mutagenicity tests.

Table 7 Characteristics and structures of thermoset resin for powder coating paints

Thermoset resins			
Resin	Functionality	Structure	Characteristics
Acrylic resins	Hydroxyl, carboxyl, epoxy, random functional group distribution		Hydrocarbon backbone
Epoxy resins	Epoxy groups, terminal functional groups		Ether linkages
Polyester resins	Hydroxyl, carboxyl, terminal functional groups		Ester linkages, heteroatom and hydrocarbon backbone

Source: Polymer Science Learning Center (2005)

Table 8 Common resin/hardener combinations employed in powder coating paints

Epoxy	Resin	Epoxy
	Hardener	Dicyandiamide and variations, Anhydrides, e.g. benzophenone tetracarboxylic dianhydride (BTDA), and Amines, e.g. 4,4'-sulfonyldianiline (DDS) 4,4'-methylenedianiline (MDA)
Polyester/epoxy (hybrid)	Resin	Carboxyl polyester
	Hardener	Epoxy
Polyester (TGIC)	Resin	Carboxyl polyester
	Hardener	Triglycidyl isocyanurate (TGIC)
Polyurethane	Resin	Hydroxyl polyester
	Hardener	Blocked isocyanate, e.g. isophorone diisocyanate (IPDI)
Acrylic	Resin	Carboxyl, hydroxyl, or glycidyl acrylics
	Hardener	TGIC, blocked isocyanate or self curing acrylics

Source: Polymer Science Learning Center (2005)

4.2 Production process

Powder coating paints production consists of 6 main process steps as shown in Figure 5. Each process step can be described below:

1. Weighing of raw materials according to the formula and quantity for the specific production
2. Mixing of raw materials in a special mixer which will take in account the different densities of raw materials
3. Extrusion of mixed raw materials using a hot melt compounding process where it becomes a hot, homogeneous paste
4. Cooling and kibbling of the hot paste by passing through a cold rolls where it becomes a brittle film. This film is a crushed into 3-5 cm of chips diameter.
5. Milling and sieving the chips to a fine particles powder (less than 100 micron) by means of a continuous process and then sieved to remove any over size powder
6. Packing of powder in cartons of 20 or 25 kg, then send to store for storing or shipping

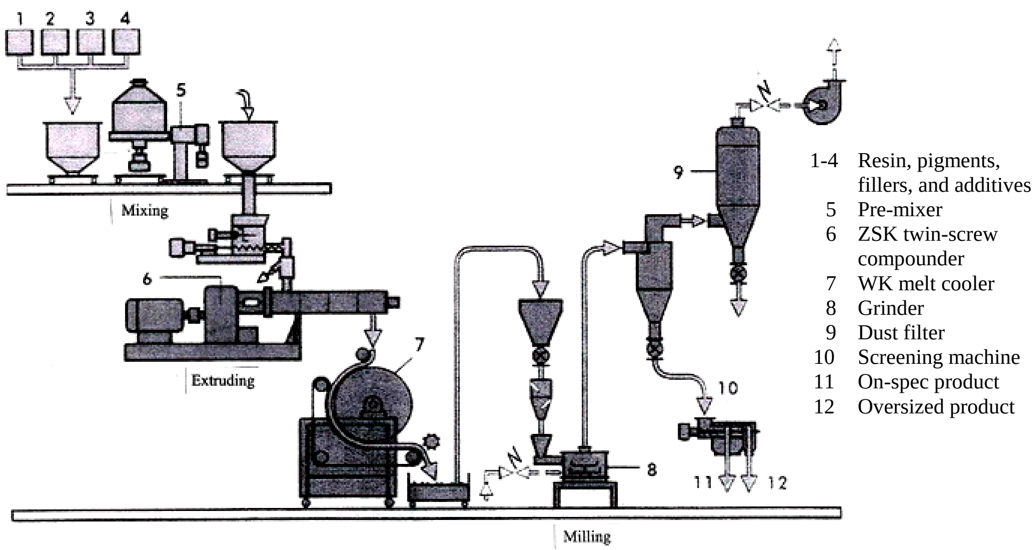


Figure 5 Powder coating paints production process

Source: Jotun Powder Coatings (2002)

4.3 Application method

A powder coating is a dry finishing process, using finely ground particles of pigment and resin that are generally electrostatic charged and sprayed onto electrically grounded parts.

There is essentially two common ways of applying powder coating; these are electrostatic spray and fluidized bed powder coating. There are several other processes that have been developed, but they are far less used. These include flame spraying, spraying with a plasma gun, airless hot spray, and coating by electophoretic deposition.

5. Paints Disposal

Due to paints as hazardous waste, therefore, paints are disposed by landfill after stabilization and solidification process. Stabilization and solidification processes are used to treat solid inorganic materials or hazardous waste including heavy metals such as chromium, vanadium, lead, cadmium and arsenic – those wastes that require effective treatment to prevent migration of heavy metals into the environment. Solid inorganic wastes contaminated with trace metals and other toxic compounds are chemically and physically stabilized by using specific recipes.

Hazardous waste may be treated to either stabilization or solidification or both, depending on the chemical and physical characteristics of the waste. Waste is first sampled and characterized in the laboratory to determine a treatment recipe. Waste is reduced to a particulate size of less than one cubic centimeter in the crushing mill. Stabilization involves addition of binders and additives to prevent hazardous contaminates from leaching into the surrounding environment. This is achieved by chemically immobilizing contaminates. Solidification uses pozzolanic reagents such as Portland cement, lime or fly ash to form solid, inert material suitable for landfill. The process is used on solid or semisolid waste. After a leachate test to ensure that they are no longer hazardous, stabilization and solidified materials are placed in a secure landfill cell (Earth Tech (Canada) Inc., 2003). Waste stabilization and solidification process flow are shown in Figure 6.

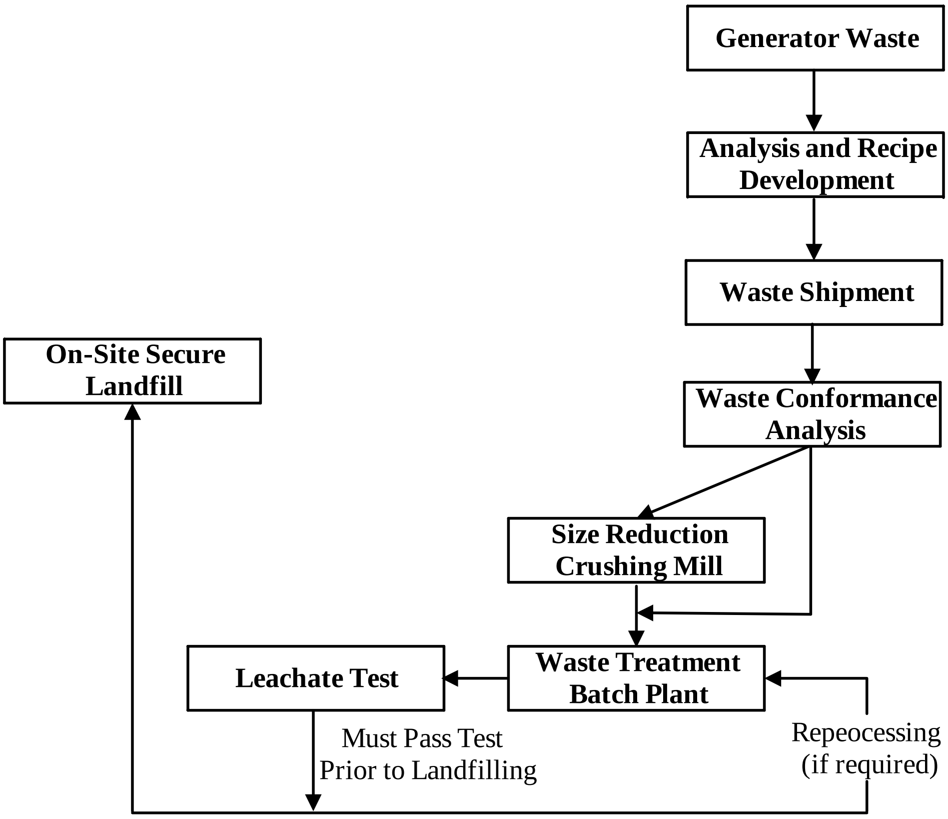


Figure 6 Waste stabilization and solidification process
Source: Earth Tech (Canada) Inc. (2003)

Environmental Impacts of Paints and Coatings

Painting or coatings process produces waste emissions to the environment as follows:

- Emission to air - VOCs from paint solvents released on drying and VOCs from paint stripping operations

- Emission to water - solvents contained in water from wet scrubbers and runoff from vehicles, ships, and aircraft bearing protective coatings with toxic metals
- Emission to solid waste - sludge from overspray collected in scrubbers, landfilling of paint containers with leftover contents, and solid waste with painted surfaces containing toxic metals

The degree of environmental impact from the manufacture of paints and coatings is small when comparing to impact from their use. The most important environmental impact from paints and coatings is the release of volatile organic compounds during the drying process after the coating is applied. In addition, the solids in a typical coating formulation are released to the air around the surface being coated. In an enclosed system, such as a paint booth, some of this emission may be captured before release to the atmosphere. Otherwise, it adds to the general atmospheric loading.

Most organics in the atmosphere have a relatively short life. Sunlight is particularly effective at bringing about the oxidation of VOCs, ultimately to carbon dioxide. But it can have some consequences on the way. In the presence of nitrogen oxides (such as are produced by combustion from such sources as vehicles and power plants), photochemically induced VOC oxidation produces ozone as a by-product. Ozone, a highly reactive form of oxygen, is a health risk at very low concentrations and is the ultimate risk factor associated with VOC emissions.

Other impacts arise from the presence of toxic solid materials in the paint formulations. These are heavy metals that can create problems long after the coating is applied. It is difficult to stop using heavy metals in the paint formulations even though know problem because it has very difficult to find substitute materials with adequate performance characteristics (Bengu, 2000).

Electric Appliance Coatings

Most of the electric appliances which coated by a paint include washing machines, dryers, freezers, air conditioners, and refrigerator. The electric appliance finish should protect the underlying metal from water, salt, detergent and other corrosive compounds acting at room to moderately elevated temperatures.

Coating process of electric appliances involves several key steps: cleaning, metal treatment, and application of paints. Cleaning of metal is the most critical step in the coating process and has received attention only recently. It has been found that when using alkaline cleaners, wash temperature plays an important role. At too low wash temperatures, some of the oils are below their melting temperatures and are thereby difficult to remove. For phosphating in metal treatment process, iron and zinc phosphates have been found suitable. Zinc phosphate is preferred where severe environments are encountered and are applied at 180-210 mg/ft^2. Iron phosphate, on the other hand, is used where lower corrosion resistance can be tolerated and is applied at 70-100 mg/ft^2 (Bengu, 2000).

Literature Related with LCA of Paints

Dobson, I.D. (1995) studied the life cycle assessment of car painting. The comparison of environmental impacts for painting a car using two alternative methods included water-based paints and solvent-based paints with end of pipe controls for VOC (incineration of VOC emissions) was investigated. An important point of this study was that it has arranged analysis to compare the two systems with VOC emissions matched as closely as possible between the processes. This was possible by adjusting the airflow through the incinerator to just destroy the same amount of VOC as the water-based paints avoids through its lower VOC content. The results from assessment were indicated that the two paint systems were environmentally similar. Therefore, selection of paint use between these systems for painting a car depended on cost and performance grounds when environmental impact of two paint systems were quite similar.

Axelsson *et al*. (1999) evaluated the environmental impacts of paint which were investigated by LCA technique. This study was divided into two parts. The first part studied LCA of paints production. For this part, solvent-based varnish, powder coating paints and solvent-based alkyd were considered. Three types of paint have different of usage characteristic which solvent-based varnish, powder coating paints, solvent-based alkyd were used on the timber, metal parts, and outdoor, respectively. The functional unit of this study was 1 kg of paint. This research considered four impact categories which were greenhouse effect, ozone layer depletion, acidification, and eutrophication. The analysis results were shown in the table 9. When comparing environmental impacts of those paints in each impact categories, it was indicated that greenhouse effect, acidification, and eutrophication have the highest environmental impact categories affected from solvent-based varnish. While ozone layer depletion has the highest environmental impact categories affected from powder coating paints**.**

Table 9 The analysis results of three types of paints

Solvent-based varnish	Greenhouse effect (g CO_2-eq)	Ozone layer depletion (g C_2H_4-eq)	Acidification (g SO_x–eq)	Eutrophication (g PO_4-eq)
Binding agent	881.6	4.2	7.4	0.9
Solvent	1145.7	2.1	6.8	0.7
Pigment	731.4	3	9.6	0.7
Manufacture	936.7	3.1	5.6	0.4
Total	3695.4	12.4	29.4	2.7

Powder coating paints	Greenhouse effect (g CO2-eq)	Ozone layer depletion (g C_2H_4-eq)	Acidification (g SO_x-eq)	*Eutrophication (g PO_4-eq)
Binding agent	3.2	0.003	0.04	0
Filler	0.1	9.9	4.3	0
Pigment	1.1	5	5.2	0
Manufacture	0.1	5.5	0.01	0
Total	4.5	20.403	9.55	0

Note: *No analysis has been made of the eutrophicationeffect of the powder coating paints.

Table 9 The analysis results of three types of paints (Cont'd)

Solvent-based alkyd paints	Greenhouse effect (g CO_2-eq)	Ozone layer depletion (g C_2H_4-eq)	Acidification (g SO_x-eq)	Eutrophication (g PO_4-eq)
Binding agent	283.4	0.8	3.2	0.3
Filler	25.3	0.01	0.3	8.3
Solvent	63.9	0.3	1	0.1
Pigment	1293.9	0.1	14.5	0.2
Manufacture	138.8	0.3	0.9	0.1
Packaging	44.5	0.01	0.1	0.01
Total	1849.8	1.52	20	9.01

The second part of the study was the life cycle assessment of the painted product during its entire life cycle. The study has primarily been analyzed with regard to the categories that influence the environment –greenhouse effect, acidification, eutrophication, and low-level ozone (ozone layer depletion). Three types of paints, which were solvent-based varnish, powder coating paints and solvent-based alkyd, were applied to workpiece including kitchen cabinet door, metal shelving, timber weatherboarding, respectively. The functional unit of this part study was quantity of paint applied to 1 m^2 of workpiece. The results of study were found that producing workpiece caused the most environment impacts when comparing to production and application of paints.

Nielsen, C.W. (1999) evaluated the environmental impacts of three types of paints which were used for metal parts. Those paints consisted of powder coating, solvent-based, and water-based paints. The environmental impact assessment of each type paints considered 3 phases which were production, use and disposal. EDIP method was used to evaluate environmental impacts. Functional unit of this study was volume of coating or painting needed to cover a metal surface of 1 m^2. Two raw materials (the pigment TiO_2 and the hardener TGIC) was selected in this research which it completely analyzed the environmental impact.

The life cycle of three types of paints could not directly compare to find type of paint has highly environmental impacts due to lack data of raw materials production which were used for paint production. The results of study were indicated that manufacturing phase generated the most significant environmental impacts for powder coatings due to effect of allergy of TGIC hardener. While solvent-based paints and water-based paints, the most environmental impacts came from hazardous waste and power consumption and emission in use phase.

From impact assessment step of powder coating paints, TGIC hardener in manufacturing phase was main cause which generated the environmental impacts. Thus, changing hardener was best alternative for reduced the environmental impact. TGIC was substituted by beta-hydroxyalkylamide, which may be less harmful to the environment.

Papasavva *et al.* (2001) evaluated the total environmental impact of the manufacturing of materials which were used for painting of a vehicle based on life cycle analysis (LCA). Materials for coating automotive in each time including three types were primers, basecoat, and clearcoat. This study considered three different painting scenarios: (a) solventborne primer, waterborne basecoat, and solventborne clearcoat; (b) powder primer, waterborne basecoat, and solventborne clearcoat; (c) powder primer, waterborne basecoat, and powder clearcoat. The LCA of each paint formulation included the environmental emissions associated with mining and production of the raw materials, production of energy required to mine and produce raw materials and final product, mining of fossil fuels required to produce energy to run the mining and manufacturing processes, and transportation of raw materials to manufacturing plant.

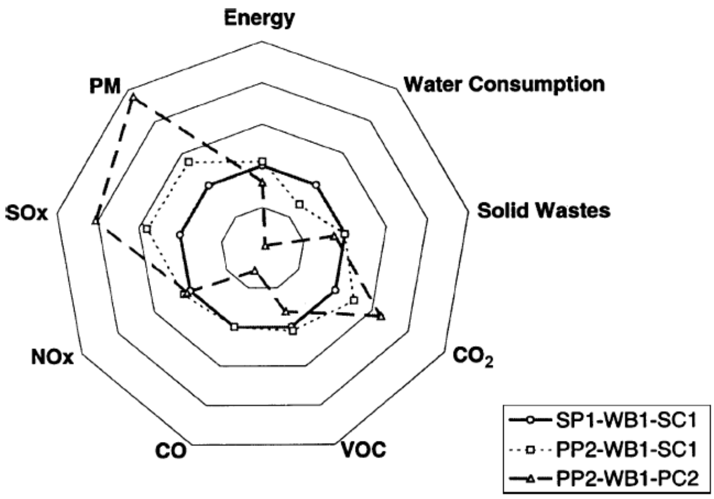


Figure 7 Single chart of the environmental performance for paint scenarios

Source: Papasavva *et al*. (2001)

The environmental performance of material production for the three scenarios was summarized in a single chart as shown in Figure 7. The environmental impact attributes considered were energy, water consumption, solid wastes, CO_2-equivalent emissions, volatile organic compounds (VOCs), CO, NOx, SOx, and particulate matter (PM). It was observed that there was no one scenario that would favor all of the environmental impact attributes.

In manufacturing of the materials for the three painting scenarios which were considered, the powder primer, waterborne basecoat, and powder clearcoat (PP2–WB1–PC2) was associated with the least energy, water consumption, solid waste, and VOC, it exceeded other scenarios in PM, SOx, and CO_2-equivalent emissions. This study could not compare the environmental impact potentials of three painting scenarios due to no aggregate all the emissions to total environmental impacts of the emissions.

MATERIALS AND METHODS

Materials

1. A desktop computer
   Hardware Pentium 4.0/ 2.60 GHz. / Ram 512 MB
   Window and Microsoft Office XP
2. SimaPro 5.1 program

Methods

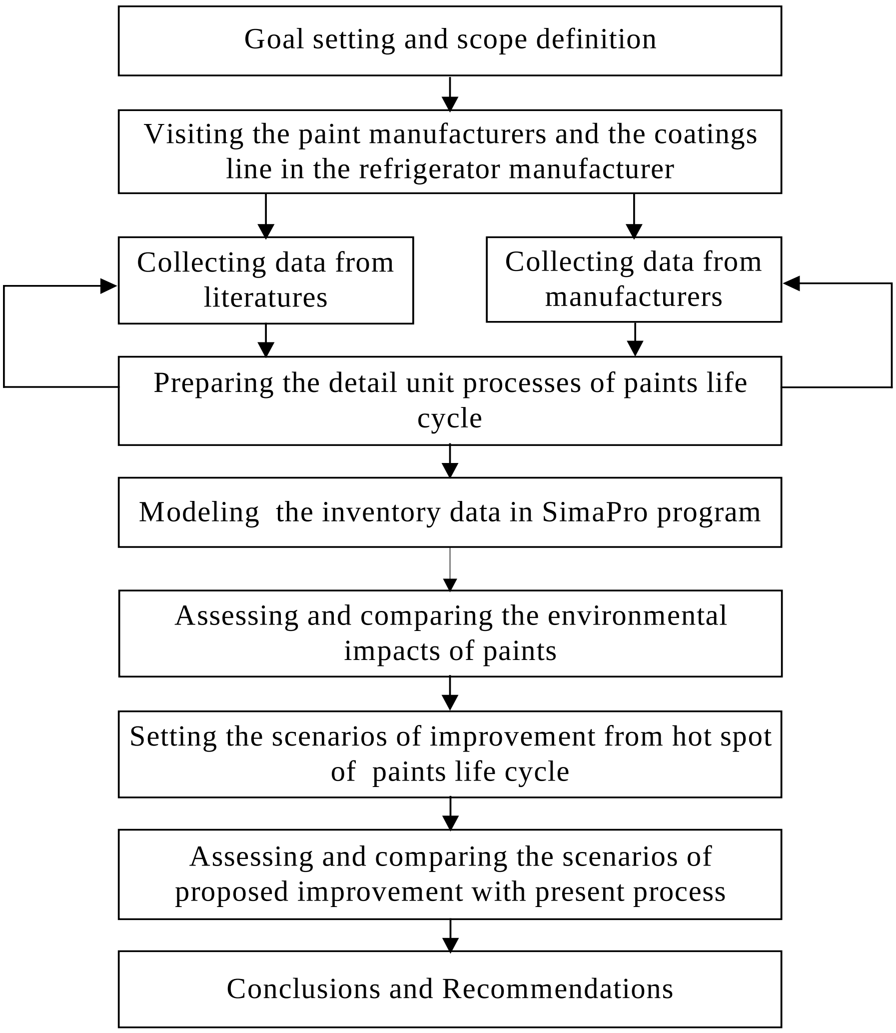


Figure 8 General methodology of the research work

1. <u>The Manufacturers Selection for the Research</u>

Due to this study as part of LCA of refrigerator which was supported by MTEC, therefore, this research evaluated the life cycle of paints which were used in refrigerator. Refrigerator, which was produced from Sanyo Universal Electric Public Company Limited (SUE), was selected as representative of these researches.

SUE provided the information relate to coating or painting process which was part of the life cycle of paints. This company was the major refrigerator manufacturer in Thailand in both local and international exporter. The refrigerator production capacity was approximately 800,000 machines per year. It was 27% of market share when total refrigerator production capacity in Thailand was approximately 3,000,000 machines per year (Electrical and Electronics Institute, 2005). As above reason, it could claim that paints which were used to the refrigerator which was produced from SUE as representative of paints in refrigerator industry of Thailand.

The 3 types of paint were used for painting the refrigerator which was produced from SUE. It consisted of solvent-based, powder coating, and water-based paints which were approximately 40%, 40%, 20%, respectively. Nippon Paint (Thailand) and Jotun Powder Coatings (Thailand) Companies were supplier of paints to SUE. Solvent-based, powder coating, and water-based paints were supplied by Nippon Paint (Thailand) company while Jotun Powder Coatings (Thailand) Company supplied only powder coating paints.

This research considered 2 types of paint including solvent-based and powder coating paints. Powder coating paints from Jotun Powder Coatings (Thailand) Company was selected as representative of powder coating paints which was used for the refrigerator because Jotun Powder Coatings (Thailand) Company was the leading powder coating manufacturers of Thailand and welcomed to provide the data. For solvent-based paints, Nippon Paint (Thailand) Company was selected as representative of solvent-based paints.

2. Research Procedures

2.1 Goal setting and scope definition

2.1.1 Goal definition

The goal of this research was to evaluate and compare the environmental life cycle impact of paints which were used for the refrigerator in Thailand.

2.1.2 Scope definition

The scope of this research could be described below:

- The functional unit of the research

In this research, 2 different types of functional units have been applied. In the first part of this research, the functional unit was set as 1 kg of paint in order to evaluate the environmental life cycle impact of paints and use as the database of paints in Thailand. In the second part, the functional unit was set as a quantity of paint applied to 1 m^2 of workpiece and used for comparing the environmental impact of three types of paints used in this research.

- Assessment criteria

The assessment criteria of impacts could be included as shown in Table 10. The environmental impacts within main categories were further divided in terms of geographic extent into global, regional, and local impacts.

Table 10 Assessment criteria in this research

Area	Environmental criteria
Global	Greenhouse effect Ozone layer depletion
Regional	Acidification Eutrophication Summer smog
Local	Heavy metals Carcinogens Energy resources Solid wastes

- System boundaries in this research

In this research, the life cycle of 2 types of powder coating paints (polyester TGIC and polyester-epoxy powder coating paints) and solvent-based paint which were used for painting the refrigerator in Thailand have been considered. The study involved the calculation of emissions to the environment resulting from the consumption of raw materials, energy utilization, manufacturing, coating, use, disposal and transportation. Furthermore, the results base on environmental impact categories have also been investigated. The improvement options through the paints life cycle could be suggested in the last part of thesis.

The life cycle boundaries of powder coating and solvent-based paints were shown in Figures 9 and 10, respectively.

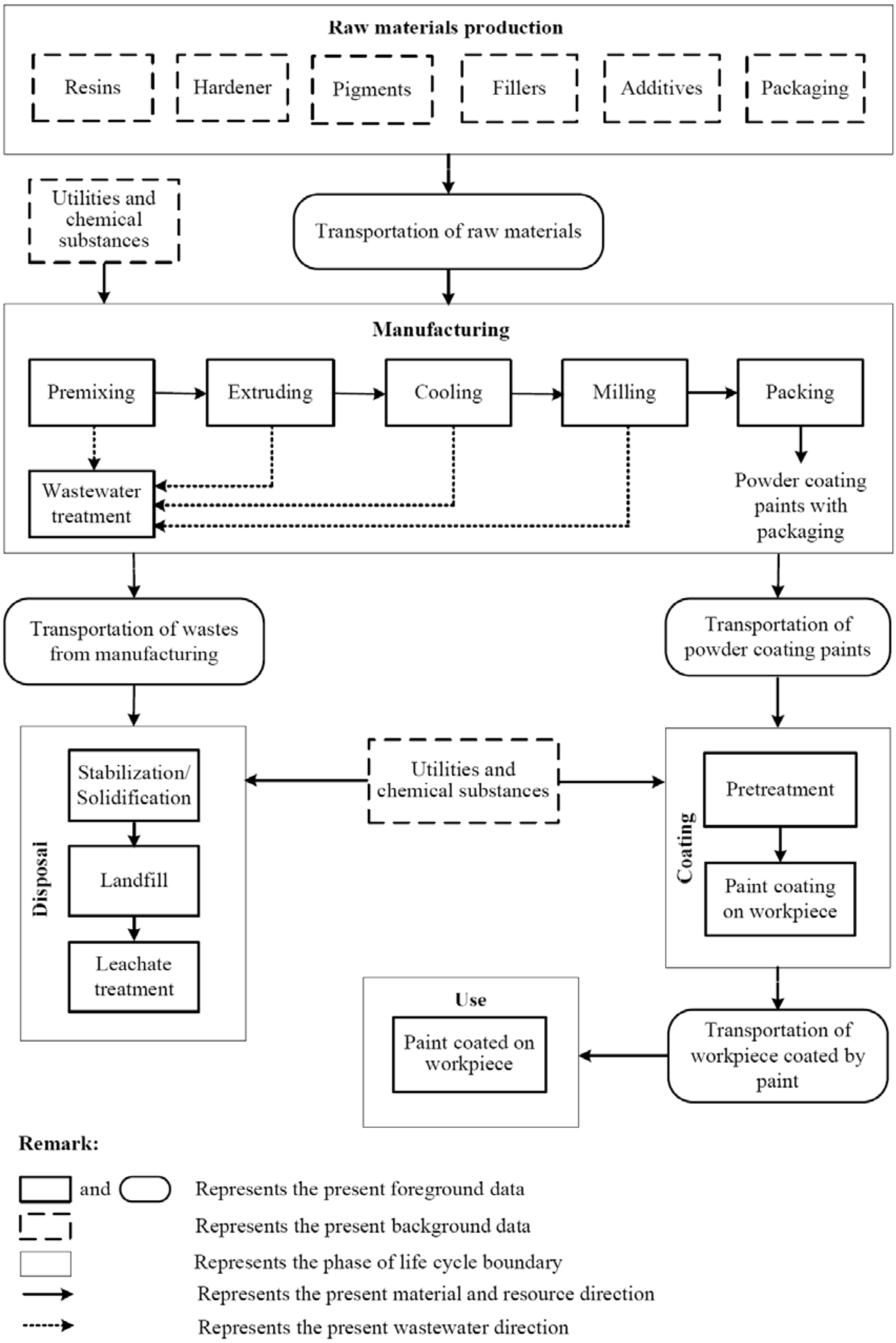


Figure 9   Life cycle boundary of powder coating paints

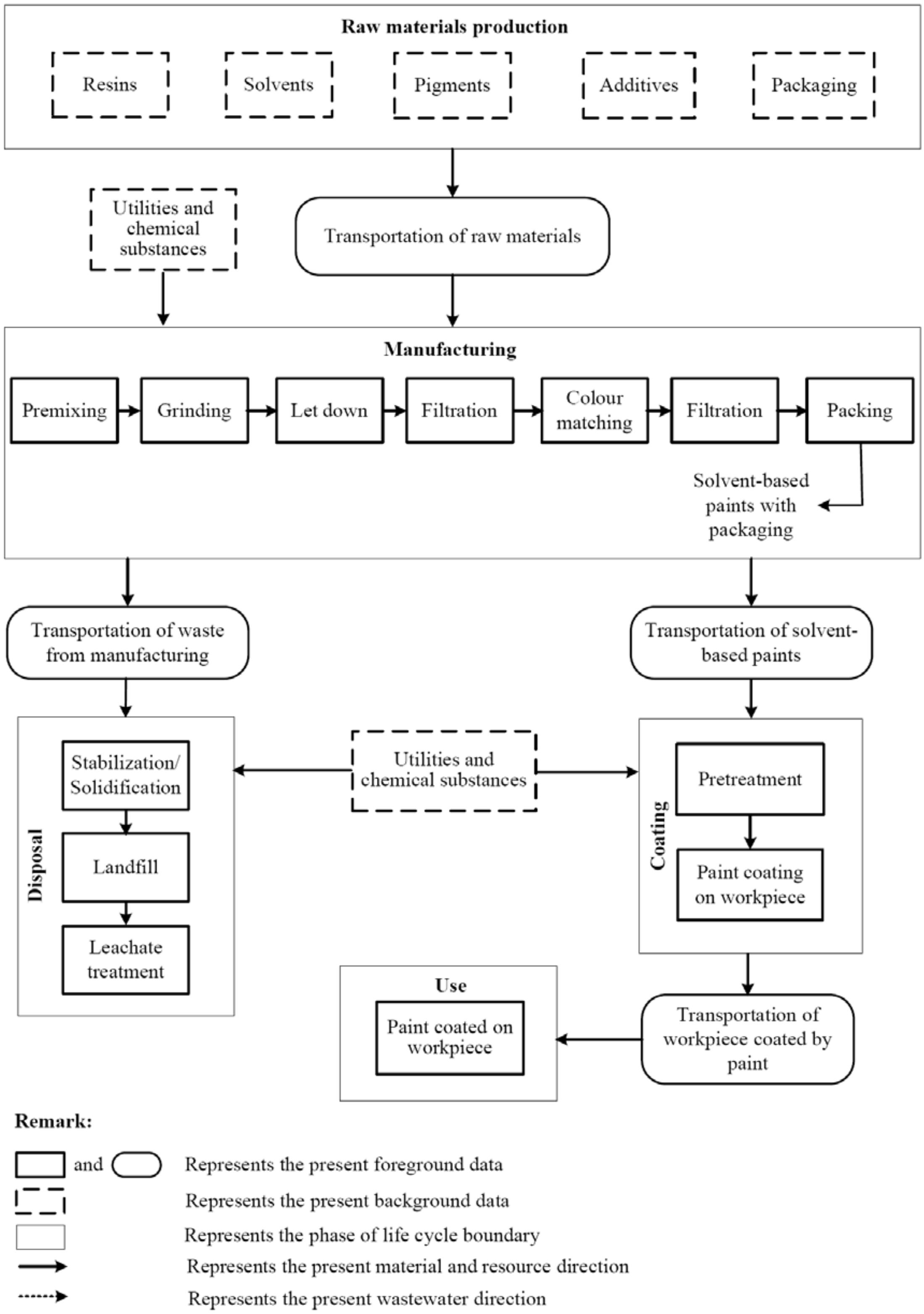


Figure 10   Life cycle boundary of solvent-based paints

From figures 9 and 10, the boundary of life cycle of paint in this research was divided into 6 phases which were raw materials production, manufacturing, coating, use, disposal, and transportation. Raw materials production phase involved all types of raw materials production, which were used to produce paints. Manufacturing phase referred to paints production, which was belonged to Jotun Powder Coating (Thailand) Company for powder coating paints and Nippon Paint (Thailand) Company for solvent-based paints. Coating phase was a step of coating workpiece with paint that this data was supported by Sanyo Universal Electric Public Company Limited (SUE). Use phase meant the use of paint coated on workpiece as the part of a refrigerator. The disposal phase related to waste disposal from manufacturing phase. Transportation phase was the transport of raw materials, paints, workpiece coated by paint, and waste from manufacturing.

- Sources of data

Sources of data were classified by unit process in the study. Input-outputs data of all unit processes in the manufacture were directly collected from the manufacturers. As the result of the time limitation, some relevant data were obtained from literatures and SimaPro database. The details of data sources were shown in the Tables 11 and 12.

Table 11 Sources of data collection in powder coating paints life cycle

Life cycle step	Manufacturer data	Literatures	SimaPro database
Raw materials production			
Resins			
- Epoxy resin			♦
- Carboxyl polyester resin		♦	♦
Hardener			
- Triglycidyl isocyanurate (TGIC)		♦	♦
Pigments			
- TiO_2			♦
- Other pigments			♦
Fillers			
- $CaCO_3$			♦
- $BaSO_4$			♦
Additives			
- Benzoin		♦	♦
Packaging			
- Linear Low Density Polyethylene			♦
- Carton box			♦
- Polyethene film			♦
Manufacturing			
- Premixing	♦		
- Extruding	♦		
- Cooling	♦		
- Milling	♦		
- Packing	♦		
- Wastewater treatment	♦		
- Utilities (water and electricity)	♦		♦
- Chemical substances		♦	♦
Coating			
- Pretreatment	♦		
- Paint coating on workpiece	♦		
- Utilities (water and electricity)	♦		♦
- Chemical substances		♦	♦

Table 11 Sources of data collection in powder coating paints life cycle (Cont'd)

Life cycle step	Manufacturer data	Literatures	SimaPro database
Use			
- Paint coated on workpiece	♦		
Disposal			
- Stabilization and solidification	♦		
- Secure landfill	♦		
- Leachate treatment	♦		
- Utilities (water and electricity)	♦		♦
- Chemical substances			♦
Transportation			
- Raw materials	♦		♦
- Powder coating paints	♦		♦
- Workpiece coated by paint	♦		♦
- Waste from manufacturing	♦		♦

Table 12 Sources of data collection in solvent-based paints life cycle

Life cycle step	Manufactory data	Literature	SimaPro database
Raw materials production			
Resins			
- Acrylic resin			♦
- Epoxy resin			♦
- Melamine formaldehyde resin			♦
Solvents			
- N-buthanol			♦
- Aromatic hydrocarbon (toluene and xylene)			♦
- Glycol ethers			♦
- Methyl isobutyl ketone			♦
Pigments			
- TiO_2			♦
- Other pigments			♦
Additives			
- Silicone rheological		♦	♦
Packaging			
- Steel drum 200 L			♦
- Steel bucket			♦
- Paper bag			♦
Manufacturing			
- Premixing	♦		
- Grinding	♦		
- Let down	♦		
- Fitration	♦		
- Colour matching	♦		
- Fitration	♦		
- Packing	♦		
- Utilities (water and electricity)	♦		♦
- Chemical substances			♦
Coating			
- Pretreatment	♦		
- Paint coating on workpiece	♦		

Table 12 Sources of data collection in solvent-based paints life cycle (Cont'd)

Life cycle step	Manufactory data	Literature	SimaPro database
Coating (Cont'd)			
- Utilities (water and electricity)	♦		♦
- Chemical substances		♦	♦
Use			
- Paint coated on workpiece	♦		
Disposal			
- Stabilization and solidification	♦		
- Secure landfill	♦		
- Leachate treatment	♦		
- Utilities (water and electricity)	♦		♦
- Chemical substances			♦
Transportation			
- Raw materials	♦		♦
- Solvent-based paints	♦		♦
- Workpiece coated by paint	♦		♦
- Waste from manufacturing	♦		♦

- Raw materials production

The data of raw materials production, which were used in all processes for paint production, were included in this work. The majority of raw material in paint production was the chemical substances that are resins, solvents, hardeners, pigments, and fillers. Due to time limitation of data collection and some raw materials which were also imported from foreign country, all of raw materials production data were adopted from SimaPro database and literatures. The details of all substances of raw materials production, i.e. raw materials use, resources use, energy use, and emissions were shown in Appendix B.

- Transportation of raw materials

The 10-wheel trucks and oceanic ships were used for raw materials transportation, which related to domestic and international transportations, respectively. Since no information regarding truck transportation in Thailand has been collected before, the truck of European countries in SimaPro database has been used. The raw materials transportation data was collected from paint manufactueres (Jotun Powder Coatings (Thailand) Company and Nippon Paint (Thailand) Company. The international transportation distance was calculated from Admiralty Distance Table, Harbour Department.

- Manufacturing

Powder coating paints production consisted of 5 main processes which were premixing, extruding, cooling, milling, and packing. Each process was included the input-outputs data of raw materials use, resources use, energy use, and emissions. Those data were collected from Jotun Powder Coatings (Thailand) Company.

Solvent-based paints production consisted of 7 main processes, which were premixing, grinding, let down, filtration, colour matching, filtration, and packing. Each process was included the input-outputs data of raw materials use, resources use, energy use, and emissions. Those data were collected from Nippon Paint (Thailand) Company.

- Transportation of paints

The pick-up trucks and 10-wheel trucks were used for powder coating and solvent-based paints domestic transportation. The transportation data of powder coating and solvent-based paints were collected from Jotun Powder Coating (Thailand) and Nippon Paint (Thailand) Company, respectively.

- Coating

Coating was a step of paint coating on workpieces, such as cabinet and door as parts of refrigerator. Coating phase included 2 unit processes which were the pretreatment and coating processes. The pretreatment process was significant process to ensure that the surface of an object was clean and free of any contaminants.

Pretreatment process in coating phase of powder coating and solvents-based paints were quite similar. However, coating processes of both paints had the difference. Coating process of powder coating paints was a method by which electrically charged powder coating material and spray-applied to grounded workpiece of refrigerator parts, while coating process of solvent-based paints was spray painting by air. A paint booth was used to collect overspray paint and to remove solvent fumes from the work area.

- Transportation of workpieces coated by paint (as parts of refrigerator)

The 10-wheel truck was used for refrigerator transportation in domestic area. The SimaPro database of truck of European countries has been used. The refrigerator transportation data was collected from Sanyo Universal Electric Public Company Limited (SUE).

- Use of paint coated on workpiece

This process involved the use of refrigerator in which paint has been coated on parts of refrigerator. Data of emission of paint coated on parts of refrigerator have been collected. Due to the low amount of emission and less environmental impact potentials comparing to other unit processes in the whole life cycle, this process has been neglected.

- Transportation of wastes from manufacturing

In this study, wastes from paints manufacturing were transported to disposal site by truck. The data of wastes transportation were collected from Jotun Powder Coating (Thailand) and Nippon Paint (Thailand) Company.

- Disposal

Disposal was waste eliminating process from the paint manufacturers (Jotun Powder Coatings (Thailand) Company and Nippon paints

(Thailand) Company). Disposal site was located in Map Ta Phut Industrial Estate, Rayong. It included 3 main unit processes; these were stabilization and solidification, secure landfill, and leachate treatment. For the stabilization and solidification, the waste was mixed with reagent to create a matrix, which prevented contaminants migration. Secure landfill was designed to prevent waste migration into the surrounding environment. While, leachate treatment was the process that used to treat the leachate which was formed when rainwater was contaminated as it passed through landfilled wastes.

- Electricity and water generation

The information of electricity and water generation in this research was derived from LCA database which has completely collected from Electricity Generating Authority of Thailand and Metropolitan Waterworks Authority (Thailand), respectively. The detail of electricity and water generation were shown in Appendix C.

All the details of manufacturing, coating, disposal, and transportation were shown in Chapter of results and discussion (Life cycle inventory).

2.2 Visiting the paint manufacturers and the coatings line in refrigerator manufacturer

In order to understand the production processes of powder coating paint, solvent-based paint, and coating process, the first step was to visit the manufacturers and discussed with the representative of paint and refrigerator manufacturers. The information including production processes and operation, material input and output, emissions to air and water, and solid waste generation have been discussed and clarified.

2.3 Collecting data from manufacturers and literatures review

The descriptions and characteristics of each unit process were collected as follows:

2.3.1 Raw materials and resources use

The data was collected from observation of the representative manufacturer. The amount of raw materials and resources use in some processes was assessed from the production data.

2.3.2 Electricity consumption

The electricity consumption data was calculated from power of each equipment in each cycle time of product, the energy unit which was used in this study for SimaPro 5.1 software was kWh.

2.3.3 Wastewater and solid waste generation

The amount of wastewater from cleaning processes in paint manufacturers was obtained from an inspection of representative manufacturer and from the record of factory profile. The wastewater from cleaning processes was sampling one month per times at the discharging locations after treated by the wastewater treatment system. The wastewater samples were analyzed corresponding to the Standard Method by Eastern Thai Consulting 1992 Co., Ltd. for parameters such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Suspended Solids (SS), Lead, Mercury, etc.

The wastewater from coating process of solvent-based paints was obtained from the record of factory profile. The sample of wastewater from coating processes was collected at the discharging locations after paint coated on workpiece in paint booth. The wastewater samples were analyzed corresponding to the Standard Method by United Analyst and Engineering Consultant Co., Ltd for parameters such as COD, BOD, SS, Lead, Mercury, etc.

2.3.4 Air emission generation

The amount of air emission from premixing and milling processes in powder coating paints manufacturer were measured at the stack of factory by an air flow meter. Total Suspended Particulate (TSP) and lead were analyzed by gravimetric and inductively coupled plasma-atomic emission spectroscopy (ICP-AES) method, respectively at Eastern Thai Consulting 1992 Co., Ltd.

Air emission data of solvent-based paints and coating line were obtained from the manufacturer environmental monitoring report, of which the ambient air quality was examined.

2.4 Preparing the detail unit processes in life cycle of paints

After gathering the data, the next step was to prepare the flow diagram of processes which included the various unit processes in life cycle of paints. All data collecting from manufacturers, SimaPro database, and literatures were added into unit processes, the detail of flow diagram in the system boundaries was built.

2.5 Modeling the inventory data in Simapro program

In this step, all inventory data were added into SimaPro program. The accuracy of all inventory data was verified by using the principle of mass balance and energy balance. All substances in the inventory were transformed into the same unit in order to summarized into impact categories. The environmental impact potentials of the present processes and substances contributed to the impact categories were obtained. Based on the significance of impact category and SimaPro calculation, 9 environmental impact categories and their contributions have been focused as follows:

- Global warming in term of kg CO_2-equivalent
- Ozone layer depletion in term of kg CFC-11-equivalent
- Acidification in term of kg SO_2-equivalent
- Eutrophication in term of kg PO_4-equivalent
- Summer smog in term of kg C_2H_4-equivalent

➢ Heavy metals	in term of	kg Pb-equivalent
➢ Carcinogens	in term of	kg B(a)P-equivalent
➢ Energy use	in term of	Mega Joules
➢ Solid wastes	in term of	kg

2.6 Assessing and comparing the environmental impacts of paints

The results of the environmental impact potentials in the whole life cycle of 1 kg of each type of paints were assessed. The processes that greatly contributed to impact potentials were focused as the hot spots of the study. After that, some modifications were suggested. Furthermore, the environmental impact potentials of three types of paints were also compared when a quantity of paint applied to 1 m^2 of workpiece which was set as the functional unit.

2.7 Setting the scenarios of improvement from hot spot of paints life cycle

From the results of the environmental impact assessment, the scenarios of improvement were proposed. The calculated results from proposed improvement scenarios revealed the decrease of the environmental impact potentials.

2.8 Assessing and comparing the scenarios of proposed improvement with the present process

The scenarios of proposed improvement were evaluated and compared with the present process in order to obtain the suitable process. In this research, the process which had less impact to the environment was focused. The comparisons between the proposed improvement scenario and the present process were discussed for both positive and negative improvements.

RESULTS AND DISCUSSION

After defining goal and scope in the research, boundary of the study was set as guideline for collecting and qualifying all relevant data. This research was focused on assessing and comparing the impact of the entire life cycle of paints which were used for the refrigerator of which consisted of polyester TGIC powder coating, polyester-epoxy powder coating, and solvent based paints. The data consisted of raw materials and energy requirement, air emission, wastewater emission, and solid waste generation. All data collections which had been in LCA compliance were collected from paint manufacturers, coating line in refrigerator manufacturer and literature data. These data were added into SimaPro program version 5.1; the results were not only shown the environmental impacts of 1 kg of each paint life cycle, but it would also be the indicator of any processes that they were the major factors which impacted to environment. These results would be used as reference for comparing with the improvement scenarios which were proposed from the hot spot(s) of each paint life cycle to find out whether these improvement scenarios minimize environmental impacts or not. Moreover, the results were also indicated the paint type which had the less environmental impact when the 3 types of paint were conducted to compare.

This chapter was divided into three parts – life cycle inventory, environmental impact assessment, and improvement and suggestion. In the first part, it consisted of life cycle inventory of 2 types of powder coating (polyester TGIC and polyester-epoxy powder coating paints) and solvent-based paints, which were used for the refrigerator. In the second part, the environmental impact assessment of 3 types of paints was evaluated and compared by SimaPro 5.1 with Eco-indicator 95 method to figure out the hot spot(s) of each paint life cycle and the type of paint which had the less environmental impact. Finally, improvement and suggestion was proposed in the improvement scenarios or options for reducing the impact occurred in those paints.

1. Life Cycle Inventory (LCI)

In this research, the paints which were used for the refrigerator were as follows: polyester TGIC powder coating, polyester-epoxy powder coating, and solvent-based paints. The life cycle of paint consisted of 6 phases: raw materials production, manufacturing, coating, use, disposal, and transportation.

The details of input-output data in each phase were shown in this part (Life Cycle Inventory) except transportation phase that the data was exhibited in form of transportation information including distance and types of vehicle. Material balance played extremely the important role because the accuracy of data affected the results obtained from the evaluation of an environmental impact in the impact assessment step.

The input-output data of paint production which were supported by paint manufacturers was mostly completed in the detail. It included the type and quantity of raw materials, energy and water consumption, type and quantity of packaging, and all emissions, however the amount of wastewater was not available. Therefore, the material balance of manufacturing phase was based on the conservation of mass assumed that the amount of wastewater or water output was equal to the amount of water consumption or water input added with the amount of imbalanced raw materials of during the production processes.

For the coating phase of powder coating and solvent-based paints including the pretreatment and coating processes, the data was collected in a form of overall processes of coating plant in refrigerator manufacturer. Therefore, the input-output data were allocated by the fraction of paint coated on workpiece. The results from data collation showed that the water output could be classified into wastewater (70%) and water vaporized during process (30%). Therefore, the amount of wastewater in coating phase was 70% of amount of water consumption or water input.

In the disposal phase, the data from the report of Monitoring and Giving Suggestion in 2004 of General Environmental Conservation Public Company Limited or GENCO of which made by the Energy and Environmental Engineering Center, Kasetsart University was used. This data included types and quantities of all chemicals and emissions for managing hazardous wastes.

1.1 Polyester TGIC powder coating paint inventory

Raw materials production phase

Raw materials which were required for polyester TGIC powder coating paint production consisted of carboxyl polyester resin, triglycidyl isocyanurate as hardener; $BaSO_4$ and $CaCO_3$ as fillers; TiO_2 and other pigments as pigments; and benzoin as representative of additives. Raw materials production data were obtained from SimaPro database and literatures, in which the details were shown in Appendix B.

Manufacturing phase

In this stage, all raw materials were transported by truck in domestic and ship in international to the manufacturing site at Jotun Powder Coatings (Thailand) Company Ltd. There were six step by step processes for producing polyester TGIC powder coating paint as follows:

- Premixing: homogenously mixed the raw materials which were used in paint manufacturing with mixer
- Extruding: extruded the raw materials which were mixed already from premixing with thermal
- Cooling: cooled paint in a paste form into a granule form
- Milling: milled a granule form into the powder of required size
- Packing: packed the powder for storage and transportation
- Wastewater treatment: treated the wastewater which was occurred from washing process in production plant

Polyester TGIC powder coating paint production processes were shown in Figure 11.

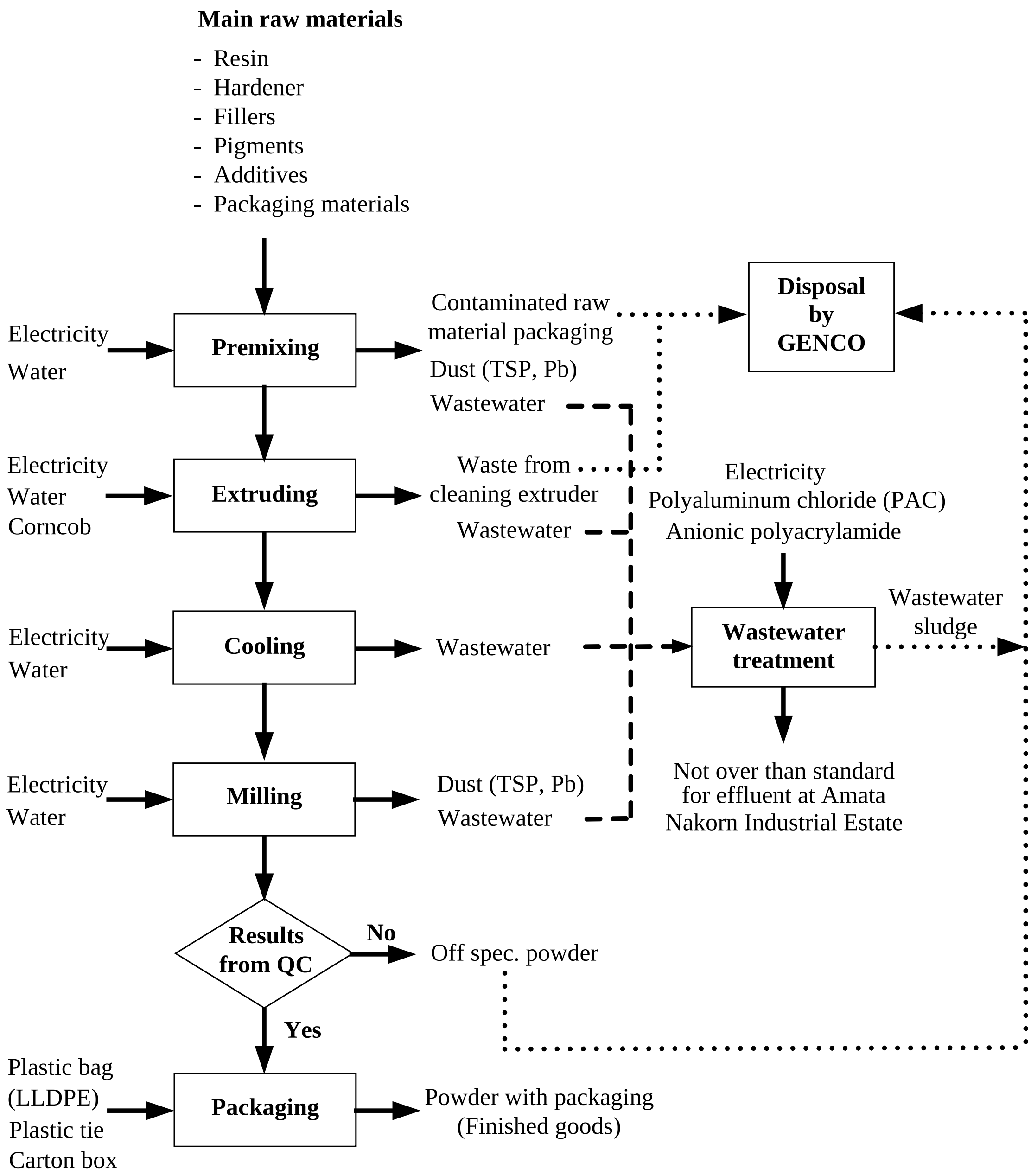


Figure 11 Polyester TGIC powder coating paint production processes

Due to the confidential powder coating paint manufacturer's data, the data were shown as the overall processes of input-output for producing 1 kg of polyester TGIC powder coating paint. The collected manufacturer data were as follows:

Input

- **Raw materials**

Carboxyl polyester resin	0.5790	kg
Triglycidyl isocyanurate (TGIC)	0.0423	kg
$BaSO_4$	0.0727	kg
$CaCO_3$	0.0873	kg
TiO_2	0.2631	kg
Other pigments	0.0004	kg
Benzoin	0.0085	kg

- **Utilities**

Electricity	0.2670	kWh
Water	7.46×10^{-4}	m^3
Corncob	4.15×10^{-3}	kg

- **Wastewater treatment substances**

$Al_2(OH)_5Cl$	1.25×10^{-4}	kg
Anionic polyacrylamide	2.80×10^{-7}	kg

- **Packaging materials**

Polyethene film	0.0090	kg
Carton box	0.0350	kg
Plastic bag (LLDPE)	0.00475	kg
Plastic tie	0.00025	kg

Output

- **Product**

Polyester TGIC powder coating paint	1	kg
Packaging	0.04	kg

- **Solid waste generation**

Contaminated raw materials packaging	0.0097	kg
Wastes from extruder cleaning	0.0205	kg
Wastewater sludge	0.0033	kg
Off-spec. powder	0.0175	kg

- **Emission to water**

Wastewater and contaminants	7.6146×10^{-4}	m^3
pH	7.3	
Biochemical Oxygen Demand (BOD)	10.92	mg
Chemical Oxygen Demand (COD)	66.13	mg
Chloride	650.01	mg
Chlorine (Residual)	0.076	mg
Total Kjedahl Nitrogen (TKN)	4.29	mg
Cyanide	0.00457	mg
Fluoride ions	0.076	mg
Barium	0.2	mg
Total dissolved solids (TDS)	4.52	mg
Formaldehyde	0.15	mg
Phenols	0.16	mg
Grease & Oil	3.05	mg
Hydrogen sulfide	0.4	mg
Arsenic	0.00152	mg
Cadmium	0.015	mg
Copper	0.076	mg
Chromium trivalent	0.00381	mg
Chromium hexavalent	0.00381	mg
Iron	0.18	mg
Lead	0.099	mg
Manganese	0.019	mg
Mercury	0.000761	mg
Nickel	0.076	mg
Selenium	0.000761	mg
Zinc	0.13	mg

- **Emission to air**

Total Suspended Particulate (TSP)	9.98×10^{-5}	kg
Lead	1.91×10^{-7}	kg

Coating phase

After producing polyester TGIC powder coating paint, it was transported by truck to the refrigerator manufacturer in order to use it for paint coating on workpiece as part of refrigerator. Coating phase included two unit processes – the pretreatment and coating process, in which was shown in Figure 12.

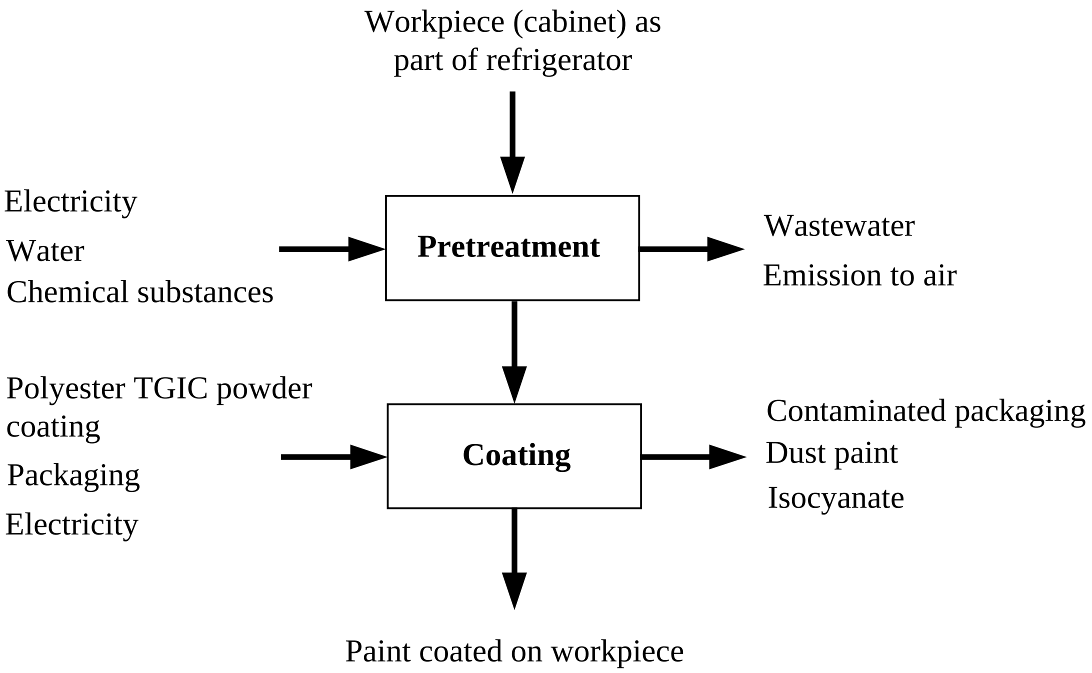


Figure 12 Coating phase of polyester TGIC powder coating paint

Input-output of coating phase when 1 kg of polyester TGIC powder coating paint was used for coating workpiece was collected as follows:

Input

- **Powder coating paint with packaging**

Polyester TGIC powder coating paint	1	kg
Packaging	0.04	kg

- **Chemical substances for pretreatment**

Surfcleaner SE-136M	1.45	kg
(as 40% NaOH, 20% Na_2CO_3, and 40% water)		

Surffine 5N-10	0.058	kg
(as 5% HNO_3 and 95% water)		
Surfdine Selec 1000 M	2.032	L
Starter # 7	0.174	L
(as 15% chlorate solution and 85% water)		
Primer # 40	0.987	L
(as 30% NaOH and 70% water)		
Toner # 30	0.029	L
Alsurf 1200 P	0.087	kg
Alsurf 1200 L	0.087	kg
➢ **Utilities**		
Electricity	8.56	kWh
Water	58.1	L

Output

➢ **Product**		
Paint coated on workpiece	0.90	kg
➢ **Solid waste generation**		
Contaminated packaging	0.04	kg
➢ **Emission to water**		
Wastewater and other materials	40.6	L
➢ **Emission to air**		
Zinc	0.02	mg
NaOH	0.25	mg
H_3PO_4	0.01	mg
CrO_3	0.02	mg
Dust paint	0.10	kg
Isocyanate as CN^-	0.02	mg

Note: The explanation in the bracket noted as "(as…)" was the material selected to use as representatives for impact assessment calculation.

Use phase

When the workpiece (cabinet) as part of the refrigerator was coated with polyester TGIC powder coating paint, it was assembled with other parts to produce the refrigerator. During refrigerator usage, an emission from paint coated on cabinet was concerned as usage. There were no input data or resource uses for this phase because the general objectives of coating paint on cabinet were for protection of the rust and decoration of the cabinet. Generally, the emissions from paint coated on cabinet throughout the usage of refrigerator were very low, thus this phase could be neglected.

Disposal phase

Solid wastes from producing polyester TGIC powder coating were the hazardous wastes that were transported by truck to the disposal site. It was located at Map Ta Phut Industrial Estate, Rayong province. Wastes from the powder coating paint manufacturer were properly managed with specific method that included 3 unit processes – stabilization and solidification, secure landfill, and leachate treatment. Scheme of overall processes was shown in Figure 13.

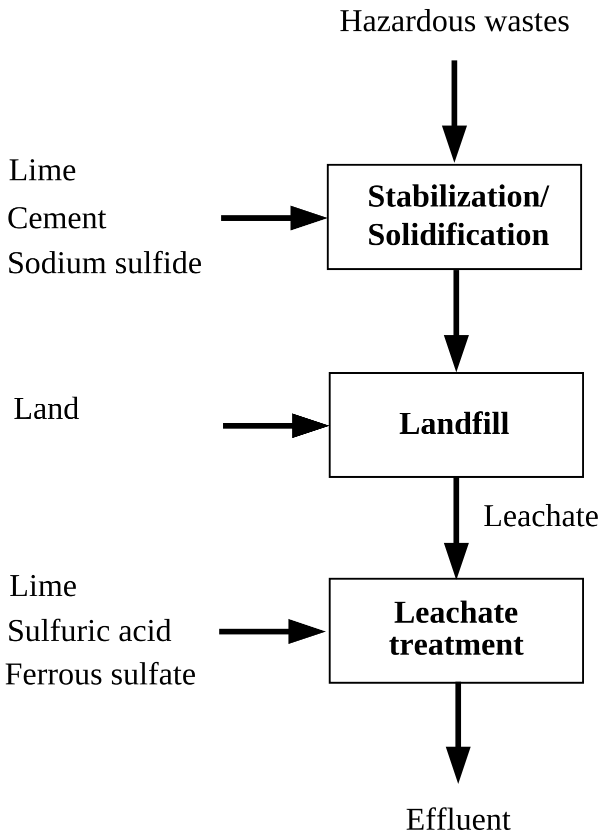


Figure 13 Hazardous wastes disposal phase

Since the production of 1 kg of polyester TGIC powder coating paint produced 0.051 kg of hazardous wastes. Therefore, the inventory for managing of 0.051 kg of hazardous wastes was collected as follows:

Input

Hazardous wastes	0.051	kg
Lime	1.61×10^{-3}	kg
Cement	2.30×10^{-3}	kg
Sodium sulfide	3.37×10^{-5}	kg
Sulfuric acid	1.20×10^{-5}	kg
Ferrous sulfate	2.79×10^{-6}	kg
Land	9.06×10^{-5}	m^2

Output

- **Emission to water**

Chemical Oxygen Demand (COD)	0.065	g
Biochemical Oxygen Demand (BOD)	6.78×10^{-4}	g
Suspended solids (SS)	8.99×10^{-4}	g
Total dissolved solid (TDS)	0.192	g
Cadmium	9.69×10^{-7}	g
Chromium	1.55×10^{-6}	g
Copper	2.52×10^{-6}	g
Manganese	5.81×10^{-7}	g
Lead	1.47×10^{-6}	g
Zinc	3.37×10^{-6}	g

Transportation phase

In this research, the transportation phase included all parts of the transportation in life cycle of polyester TGIC powder coating paint. The detail of transportation was shown in Table 13.

Table 13 Transportation data in the whole life cycle of polyester TGIC powder coating paint

Types	Producer to user site	Distance	Transport by
Carboxyl polyester resin	Taiwan to Chonburi	2,941.9 km	Container ship
	Rayong to Chonburi	98 km	10-wheel truck
Triglycidyl isocyanurate	Germany to Chonburi	15,864.9 km	Container ship
$BaSO_4$	Rayong to Chonburi	98 km	10-wheel truck
$CaCO_3$	Rayong to Chonburi	98 km	10-wheel truck
TiO_2	Australia to Chonburi	5,211.1 km	Container ship
Other pigments	Australia to Chonburi	5,211.1 km	Container ship
Benzoin	Bangkok to Chonburi	81 km	10-wheel truck
Polyester powder coating	Chonburi to Kabinburi	155 km	6-wheel truck
Workpiece coated by paint	Kabinburi to Bangna	187 km	6-wheel truck
	Distrubutor	180 km	6-wheel truck
Hazardous wastes	Chonburi to Rayong	98 km	10-wheel truck

1.2 Polyester-epoxy powder coating paint inventory

Raw materials production phase

Raw materials which were used for polyester-epoxy powder coating paint process were similar to those of polyester TGIC powder coating paint (as mentioned in section 1.1), except that of the hardener. In this process, epoxy resin was used as the hardener. Raw materials production data were obtained from SimaPro database and literatures as the detail shown in Appendix B.

Manufacturing phase

Polyester-epoxy powder coating paint production process was quite similar to those of polyester TGIC powder coating paint as shown in Figure 11. The overall input-output for producing 1 kg of polyester-epoxy powder coating paint process was collected as follows:

Input

- **Raw materials**

Carboxyl polyester resin	0.3053	kg
Epoxy resin	0.3055	kg
$BaSO_4$	0.0651	kg
$CaCO_3$	0.0781	kg
TiO_2	0.2905	kg
Other pigments	0.0005	kg
Benzoin	0.0085	kg

- **Utilities**

Electricity	0.267	kWh
Water	7.46×10^{-4}	m^3
Corncob	4.15×10^{-3}	kg

- **Wastewater treatment substances**

$Al_2(OH)_5Cl$	1.24×10^{-4}	kg
Anionic Polyacrylamide	2.80×10^{-7}	kg

- **Packaging materials**

Polyethene film	0.0090	kg
Carton box	0.0350	kg
Plastic bag (LLDPE)	0.00475	kg
Plastic tie	0.00025	kg

Output

- **Product**

Polyester-epoxy powder coating paint	1	kg
Packaging	0.04	kg

- **Solid waste generation**

Contaminated raw materials packaging	0.0097	kg
Wastes from extruder cleaning	0.0205	kg
Wastewater sludge	0.0033	kg
Off-spec. powder	0.0175	kg

- **Emission to water**

Wastewater and contaminants	7.6166×10^{-4}	m^3
pH	7.3	
Biochemical Oxygen Demand (BOD)	10.92	mg
Chemical Oxygen Demand (COD)	66.14	mg
Chloride	650.18	mg
Chlorine (Residual)	0.076	mg
Total Kjedahl Nitrogen (TKN)	4.30	mg
Cyanide	0.00457	mg
Fluoride ions	0.076	mg
Barium	0.198	mg
Total dissolved solids (TDS)	353.79	mg
Suspended solids (SS)	4.52	mg
Formaldehyde	0.15	mg
Phenols	0.16	mg
Grease & Oil	3.05	mg
Hydrogen sulfide	0.4	mg
Arsenic	0.00152	mg
Cadmium	0.015	mg
Copper	0.076	mg
Chromium trivalent	0.00381	mg
Chromium hexavalent	0.00381	mg

Iron	0.18	mg
Lead	0.099	mg
Manganese	0.019	mg
Mercury	0.000762	mg
Nickel	0.076	mg
Selenium	0.000762	mg
Zinc	0.13	mg

- **Emission to air**

Total Suspended Particulate (TSP)	9.98×10^{-5}	kg
Lead	1.91×10^{-7}	kg

Coating phase

In this phase, the same data of polyester TGIC powder coating paint as mentioned in Section 1.1 (Fig. 12) were used because of their similar coating method. The input-output of coating phase was collected as follows:

Input

- **Powder coatings with packaging**

Polyester-epoxy powder coating paint	1	kg
Packaging	0.04	kg

- **Chemical substances for pretreatment**

Surfcleaner SE-136M	1.45	kg
(as 40% NaOH, 20% Na_2CO_3, and 40% water)		
Surffine 5N-10	0.058	kg
(as 5% HNO_3 and 95% water)		
Surfdine Selec 1000 M	2.032	L
Starter # 7	0.174	L
(as 15% chlorate solution and 85% water)		
Primer # 40	0.987	L
(as 30% NaOH and 70% water)		
Toner # 30	0.029	L

Alsurf 1200 P	0.087	kg
Alsurf 1200 L	0.087	kg
➢ **Utilities**		
Electricity	8.56	kWh
Water	58.1	L

Output

➢ **Product**		
Paint coated on cabinet	0.90	kg
➢ **Solid waste generation**		
Contaminated packaging	0.04	kg
➢ **Emission to water**		
Wastewater and other materials	40.6	L
➢ **Emission to air**		
Zinc	0.02	mg
NaOH	0.25	mg
H_3PO_4	0.01	mg
CrO_3	0.02	mg
Dust paint	0.10	kg
Isocyanate as CN^-	0.02	mg

Note: The explanation in the bracket noted as "(as…)" was the material selected to use as representatives for impact assessment calculation.

Use phase

As mentioned in the use phase of paint coated on workpiece of polyester TGIC powder coating paint, therefore, input-output regarding the process could be neglected.

Disposal phase

Types of the solid wastes from polyester-epoxy powder coating paint were analogous to those of polyester TGIC powder coating paint. Therefore, the disposal phase data of polyester TGIC powder coating was again used in this disposal phase.

Transportation phase

Table 14 showed the detail of transportation in the entire life cycle of polyester-epoxy powder coating.

Table 14 Transportation data in the whole life cycle of polyester-epoxy powder coating paint

Types	Producer to user site	Distance	Transport by
Carboxyl polyester resin	Taiwan to Chonburi	2,941.9 km	Container ship
	Rayong to Chonburi	98 km	10-wheel truck
Epoxy resin	Taiwan to Chonburi	2,941.9 km	Container ship
	Rayong to Chonburi	98 km	10-wheel truck
$BaSO_4$	Rayong to Chonburi	98 km	10-wheel truck
$CaCO_3$	Rayong to Chonburi	98 km	10-wheel truck
TiO_2	Australia to Chonburi	5,211.1 km	Container ship
Other pigments	Australia to Chonburi	5,211.1 km	Container ship
Benzoin	Bangkok to Chonburi	81 km	10-wheel truck
Polyester-epoxy powder coating	Chonburi to Kabinburi	155 km	6-wheel truck
Workpiece coated by paint	Kabinburi to Bangna	187 km	6-wheel truck
	Distrubutor	180 km	6-wheel truck
Hazardous wastes	Chonburi to Rayong	98 km	10-wheel truck

1.3 Solvent-based paint inventory

Raw materials production phase

Raw materials which were required for solvent-based paint production mainly consisted:

1. Resins including acrylic, epoxy, and melamine formaldehyde
2. Solvents including n-buthanol, xylene, aromatic hydrocarbons, butyl glycol ether, and methyl isobutyl ketone
3. Pigments including TiO_2 and other pigments
4. Additives including silicone rheological

Raw materials production data were obtained from SimaPro database and literatures as the detail shown in Appendix B.

Manufacturing phase

Nippon paint (Thailand) Co., Ltd. was the main producer of solvent-based paint production which was supplied to the refrigerator production industries in Thailand. The overall processes were generally comprised 7 processes including: premix, grinding, let down, filtration, colour matching, filtration, and packing. Figure 14 expressed the overall processes in the solvent-based paint production.

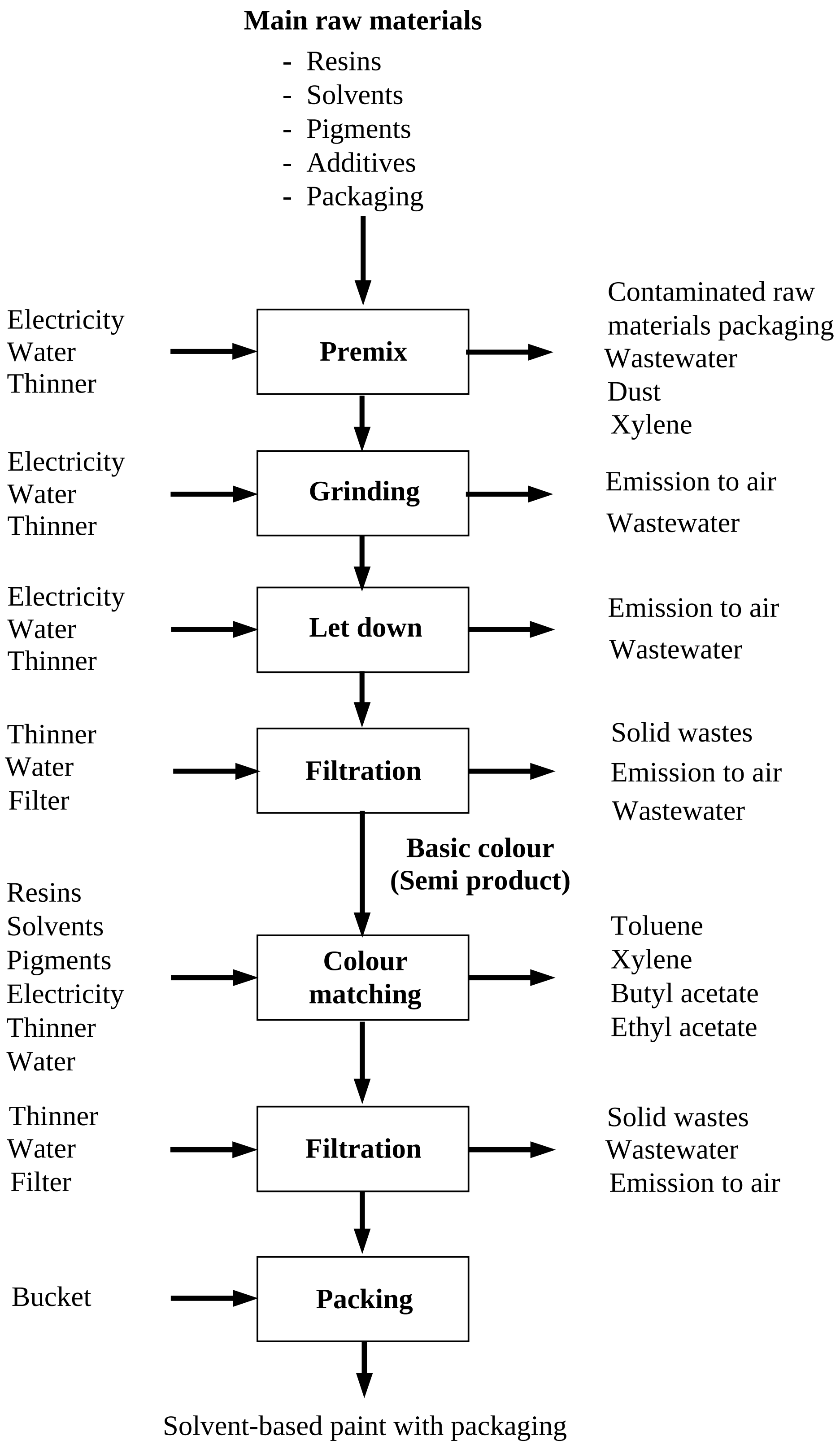


Figure 14 Solvent-based paint production processes

The confidential data of solvent-based paint manufacturing was shown in a form of input-output of 1 kg solvent-based paint processes as follows:

Input

- **Raw materials**

<u>Resins</u>		
Acrylic resin	0.3519	kg
Epoxy resin	0.0368	kg
Melamine formaldehyde resin	0.0923	kg
<u>Solvents</u>		
N-buthanol	0.0386	kg
Xylene	0.0102	kg
Aromatic hydrocarbon	0.1078	kg
(C9-C11 as dialkylbenzenes, trialkylbenzenes, and alkylbenzenes)		
Butyl glycol ether	0.0855	kg
Methyl isobutyl ketone	0.0029	kg
<u>Pigments</u>		
TiO_2	0.2761	kg
Other pigments	0.0003	kg
<u>Additives</u>		
All additives	0.0077	kg
(as silicone rheological)		
<u>Raw materials packaging</u>		
Steel drum 200 L	0.0896	kg
Paper bag	0.0055	kg

- **Utilities**

Electricity	6.702	kWh
Water	2.00×10^{-4}	m^3
Thinner	0.040	kg
Nylon fabric as filter	0.005	kg

- **Packaging material**

Steel sheet (ECCS)	0.0688	kg

Output

- **Product**

Solvent-based paint	1	kg
Packaging (Steel)	0.0688	kg

- **Solid waste generation**

Contaminated raw material bag packaging	0.0058	kg
Contaminated raw material steel packaging	0.0903	kg
Nylon fabric	0.005	kg

- **Emission to water**

Wastewater and contaminants	2.49×10^{-4}	kg
pH	6.6	
Biochemical Oxygen Demand (BOD)	34.611	mg
Suspended solids (SS)	6.225	mg
Total dissolved solid (TDS)	124.749	mg
Oil & Grease	1.992	mg

Note: The explanation in the bracket noted as "(as…)" was the material selected to use as representatives for impact assessment calculation.

Coating phase

After producing solvent-based paint, it was transported by truck to refrigerator manufacturer and was used for coating on workpiece as the part of refrigerator. Coating phase was divided into 2 unit processes – the pretreatment and coating processes as shown in Figure 15.

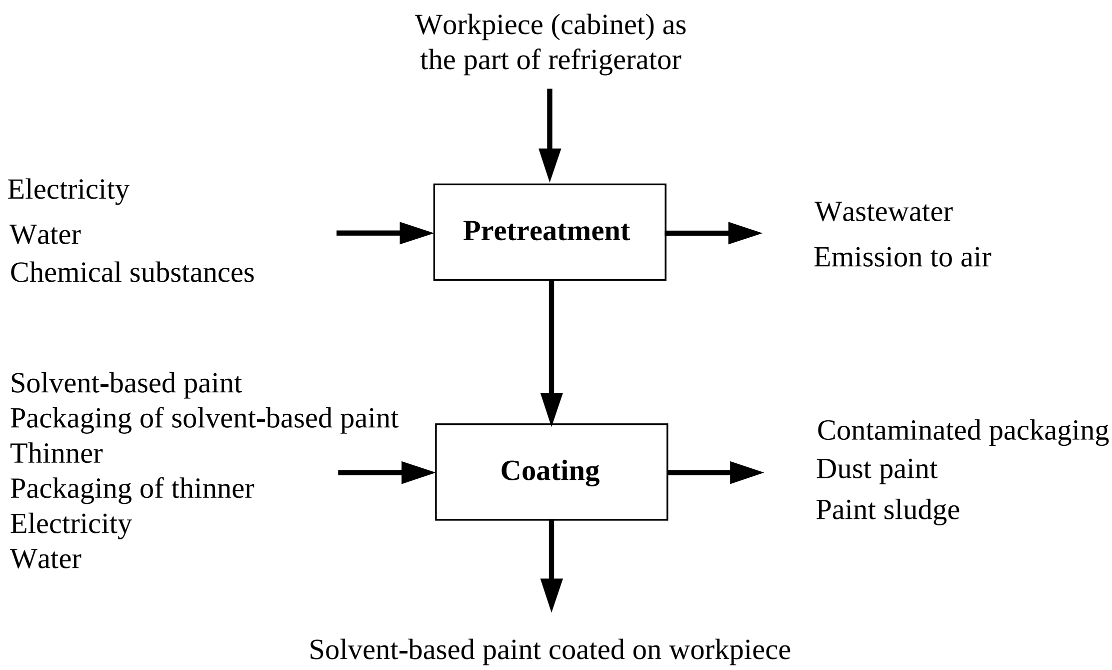


Figure 15 Coating phase of solvent-based paint

Input-output of coating phase when 1 kg of solvent-based paint was used for coating workpiece was collected as follows:

Input

- **Solvent-based paint with packaging**

Solvent-based paint	1	kg
Packaging (Steel sheet)	0.0688	kg

- **Chemical substances for pretreatment**

Surfcleaner SE-136M	1.45	kg
(as 40% NaOH, 20% Na_2CO_3, and 40% water)		
Surffine 5N-10	0.058	kg
(as 5% HNO_3 and 95% water)		
Surfdine Selec 1000 M	2.032	L
Starter # 7	0.174	L
(as 15% chlorate solution and 85% water)		
Primer # 40	0.987	L
(as 30% NaOH and 70% water)		

Toner # 30	0.029	L
Alsurf 1200 P	0.087	kg
Alsurf 1200 L	0.087	kg

- **Utilities**

Electricity	33.65	kWh
Water	454.06	L
Thinner	0.25	kg
Packaging of thinner	0.0167	kg

Output

- **Product**

Paint coated on cabinet	0.80	kg

- **Solid waste generation**

Contaminated packaging	0.0855	kg
Paint sludge	0.6710	kg

- **Emission to water**

Wastewater and other materials	317.84	kg
pH	6.4	
Biochemical Oxygen Demand (BOD)	0.2159	kg
Chemical Oxygen Demand (COD)	1.0001	kg
Total Suspended Solids (TSS)	0.0172	kg
Total Dissolved Solids (TDS)	0.1877	kg
Oil & Grease	0.0022	kg
Mercury	5.21×10^{-6}	kg
Cadmium	1.66×10^{-6}	kg
Lead	3.60×10^{-5}	kg
Arsenic	1.30×10^{-6}	kg
Chromium	5.27×10^{-6}	kg
Zinc	1.21×10^{-4}	kg
Manganese	6.04×10^{-5}	kg

- **Emission to air**

Zinc	0.02	mg
NaOH	0.25	mg
H_3PO_4	0.01	mg
CrO_3	0.02	mg
Dust paint	0.30	kg

Note: The explanation in the bracket noted as "(as…)" was the material selected to use as representatives for impact assessment calculation.

Use phase

This phase could be analogously described to those in the use phase as in Section 1.1.

Disposal phase

The solid waste disposal of solvent-based paint manufacturer was similar to the hazardous wastes disposal of powder coating paint as shown in Figure 13.

As a result, in order to produce 1 kg of solvent-based paint, 0.1011 kg of solid waste was generated. Since the contaminated raw materials packaging (200-L steel drum) that weigh 0.0903 kg was reused within the factory, so the amount of solid waste disposed was 0.0108 kg. The inventory for managing of 0.0108 kg hazardous wastes was shown as follows:

Input

Hazardous wastes	0.0108	kg
Lime	3.42×10^{-4}	kg
Cement	4.86×10^{-4}	kg
Sodium sulfide	7.14×10^{-6}	kg
Sulfuric acid	2.54×10^{-6}	kg
Ferrous sulfate	5.91×10^{-7}	kg
Land	9.06×10^{-5}	m^2

Output

- **Emission to water**

Chemical Oxygen Demand (COD)	0.014	g
Biochemical Oxygen Demand (BOD)	1.44×10^{-4}	g
Suspended solids (SS)	1.90×10^{-4}	g
Total dissolved solid (TDS)	0.041	g
Cadmium	2.05×10^{-7}	g
Chromium	3.28×10^{-7}	g
Copper	5.34×10^{-7}	g
Manganese	1.23×10^{-7}	g
Lead	3.12×10^{-7}	g
Zinc	7.14×10^{-7}	g

Transportation phase

The detail of transportation of solvent-based paint was shown in Table 15.

Table 15 Transportation data in the whole life cycle of solvent-based paint

Types	Producer to user site	Distance	Transport by
Resins	Samutprakan to Chonburi	64 km	10-wheel truck
Solvents	Middle Asia to Chonburi	4936.4 km	Container ship
Pigments	Japan to Chonburi	2594.2 km	Container ship
Additives	Japan to Chonburi	2594.2 km	Container ship
Solvent-based paint	Chonburi to Kabinburi	155 km	6-wheel truck
Workpiece coated by paint	Kabinburi to Bangna	187 km	6-wheel truck
	Distrubutor	180 km	6-wheel truck
Hazardous wastes	Chonburi to Rayong	98 km	10-wheel truck

2. Life Cycle Impact Assessment (LCIA)

After preparation and addition of life cycle inventory into SimaPro model, LCIA of the environmental impact potentials of polyester TGIC powder coating, polyester-epoxy powder coating and solvent-based paints could be evaluated and compared by using SimaPro 5.1 with Eco-indicator 95 method. The environmental impact categories which were focused in this research were as follows:

- Greenhouse effect
- Ozone layer depletion
- Acidification
- Eutrophication
- Summer smog
- Heavy metals
- Carcinogens
- Energy resources
- Solid wastes

In this research, the database of utilities including electricity and water of Thailand was used in SimaPro model. These databases have been completely collected from Electricity Generating Authority of Thailand (EGAT) and Metropolitan Waterworks Authority (Thailand). However, other databases almost came from SimaPro, particularly the raw materials which were mainly imported from foreign countries. Therefore, the utilization of utility database which was collected in Thailand could be presented the different results from those obtained using the utility database in SimaPro. Consequently, LCIA results in this part were shown in comparison both the results obtained from Thailand and SimaPro databases.

2.1 Life cycle impact assessment of polyester TGIC powder coating paint

The assessment of the environmental impact (characterization value) in the entire life cycle of 1 kg polyester TGIC powder coating paint was undertaken by using SimaPro 5.1 with Eco-indicator 95 method, covering the production of raw materials, manufacturing, coating, use, disposal, and transportation. It was found that the entire life cycle of 1 kg polyester TGIC powder coating paint contributed the environmental impact as shown in Table 16.

Table 16 The environmental impact potentials of the entire life cycle of 1 kg polyester TGIC powder coating paints obtained from two different sources of utility database

Impact category	Characterized value		Unit
	Utility database of Thailand	Utility database of SimaPro	
Greenhouse effect	32.2	11.2	kg CO_2-eq
Ozone layer depletion	9.52×10^{-6}	9.35×10^{-6}	kg CFC-11-eq
Acidification	0.184	0.0879	kg SO_2-eq
Eutrophication	0.0144	0.00614	kg PO_4-eq
Summer smog	0.26	0.0372	kg C_2H_4-eq
Heavy metals	6.92×10^{-5}	7.90×10^{-5}	kg Pb-eq
Carcinogens	1.10×10^{-5}	3.48×10^{-7}	kg B(a)P-eq
Energy resources	1420	185	MJ LHV-eq
Solid wastes	13.1	0.46	kg-eq

From Table 16, it was found that the environmental impact of the polyester TGIC powder coating used the utility database of SimaPro was less than that obtained from the utility database of Thailand in all impact categories. This was because the impacts of the electricity and water generation of foreign countries (Europe) as used in polyester TGIC powder coating was quite less than that of the electricity and water generation of Thailand.

2.1.1 Impact assessment of each phase

The overview assessment of the whole life cycle was undertaken. The impact assessment of the whole life cycle could be applied by considering all unit processes including raw materials production, manufacturing, coating, use, disposal, and transportation. The assessment results showed the environment impact of each phase and indicated a phase of which generated the highest environmental impact potentials.

The environmental impact potentials of each phase in the whole life cycle of polyester TGIC powder coating paints obtained from the use of two different sources of utility database were summarized in Tables 17 and 18. Similarly, the graphical overviews of environmental impact potentials (characterization value) constructed using two different sources of utility database were presented in Figures 16 and 17. The graphical overview of total environmental impact scores was presented in Figure 18.

Table 17 Environmental impact of each phase in the whole life cycle of 1 kg polyester TGIC powder coating paint calculated from the utility database of Thailand

Impact categories / Phases	Greenhouse effect ($kg\ CO_2$-eq)	Ozone layer depletion (kg CFC11-eq)	Acidification ($kg\ SO_2$-eq)	Eutrophication ($kg\ PO_4$-eq)	Summer smog ($kg\ C_2H_4$-eq)	Heavy metals (kg Pb-eq)	Carcinogens (kg B(a)P*-eq)	Energy resources (MJ)	Solid wastes (kg)
Raw materials production	3.46	3.16×10^{-6}	0.0215	0.00124	0.0313	1.87×10^{-5}	1.09×10^{-7}	89.5	0.290
Manufacturing	0.344	6.62×10^{-8}	0.00224	0.000183	0.0028	6.77×10^{-7}	1.33×10^{-7}	18.1	0.156
Coating	26.5	2.76×10^{-6}	0.143	0.0105	0.222	3.14×10^{-5}	1.06×10^{-5}	1280	12.6
Use	-	-	-	-	-	-	-	-	-
Disposal	0.00455	4.81×10^{-10}	1.16×10^{-5}	6.29×10^{-6}	4.24×10^{-7}	3.28×10^{-8}	3.33×10^{-11}	0.0197	0
Transportation	1.93	3.53×10^{-6}	0.0173	0.0025	0.00345	1.84×10^{-5}	7.83×10^{-8}	27.4	0
Total	32.2	9.52×10^{-6}	0.184	0.0144	0.26	6.92×10^{-5}	1.10×10^{-5}	1420	13.1

(* Benzo [a] Pyrene- it applied in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbons)

Table 18 Environmental impact of each phase in the whole life cycle of 1 kg polyester TGIC powder coating paint calculated from the utility database of SimaPro

Phases \ Impact categories	Greenhouse effect (kg CO_2-eq)	Ozone layer depletion (kg CFC11-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO_4-eq)	Summer smog (kg C_2H_4-eq)	Heavy metals (kg Pb-eq)	Carcinogens (kg B(a)P*-eq)	Energy resources (MJ)	Solid wastes (kg)
Raw materials production	3.35	3.15×10^{-6}	0.021	0.0012	0.0302	1.87×10^{-5}	1.37×10^{-7}	83.4	0.227
Manufacturing	0.112	1.06×10^{-7}	0.00133	6.76×10^{-5}	7.38×10^{-5}	1.36×10^{-6}	4.10×10^{-9}	2.27	5.81×10^{-5}
Coating	5.76	2.56×10^{-6}	0.0483	0.00237	0.00343	4.05×10^{-5}	1.29×10^{-7}	72.1	0.232
Use	-	-	-	-	-	-	-	-	-
Disposal	0.00455	4.81×10^{-10}	1.16×10^{-5}	6.29×10^{-6}	4.24×10^{-7}	3.28×10^{-8}	3.33×10^{-11}	0.0197	0
Transportation	1.93	3.53×10^{-6}	0.0173	0.0025	0.00345	1.84×10^{-5}	7.83×10^{-8}	27.4	0
Total	11.2	9.35×10^{-6}	0.0879	0.00614	0.0372	7.90×10^{-5}	3.48×10^{-7}	185	0.46

(* Benzo [a] Pyrene- it applied in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbons)

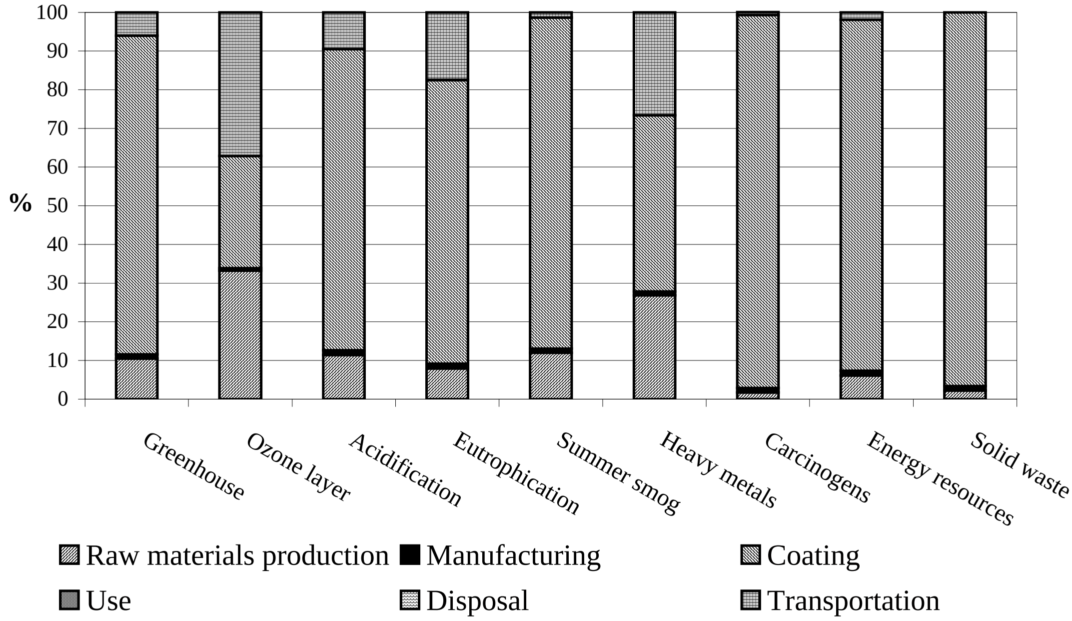


Figure 16 Contribution of the characterization value of each impact categories in polyester TGIC powder coating paint life cycle obtained from the utility database of Thailand

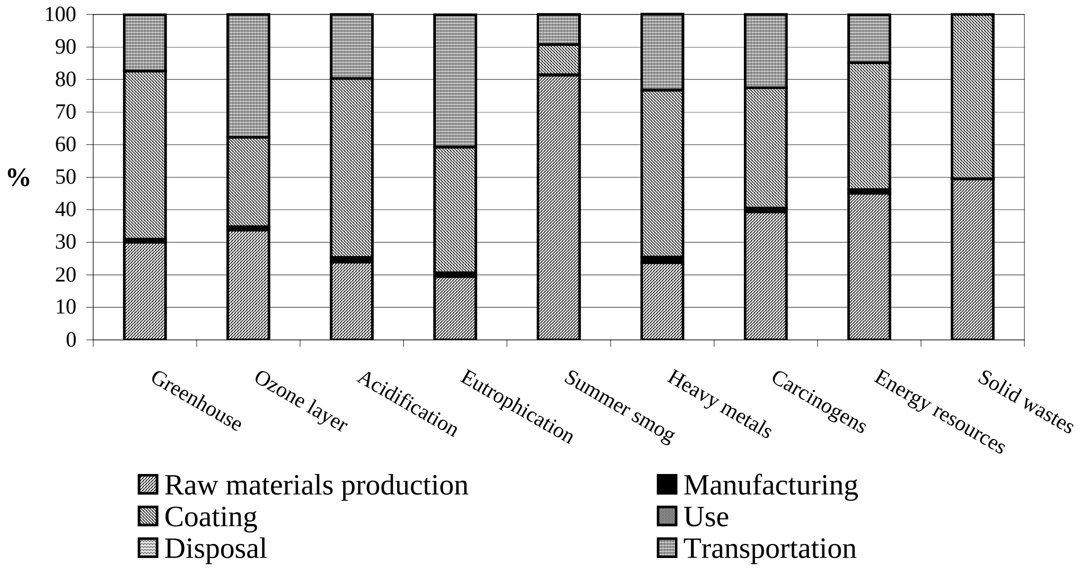


Figure 17 Contribution of the characterization value of each impact categories in polyester TGIC powder coating paint life cycle obtained from the utility database of SimaPro

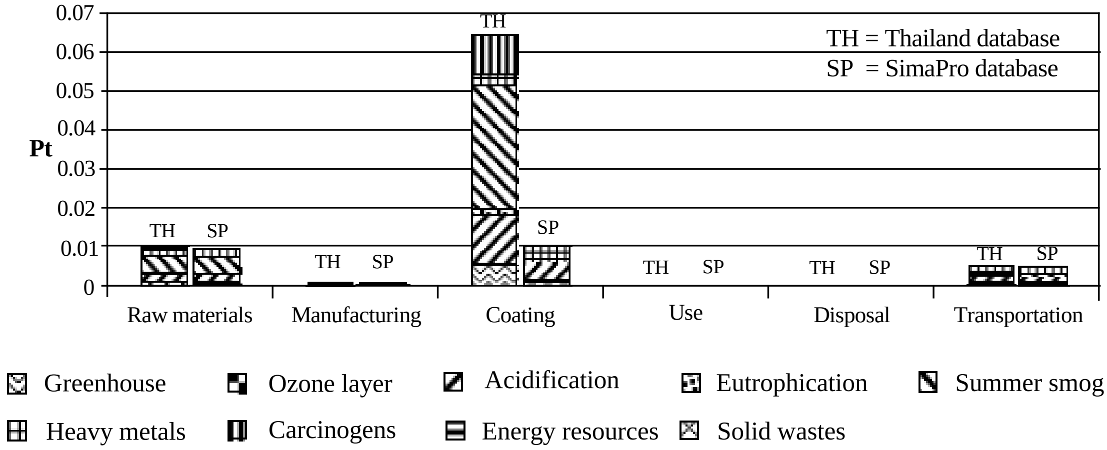


Figure 18 The total environmental impact scores of each phase in polyester TGIC powder coating paint life cycle obtained from utility databases of Thailand and SimaPro

The environmental impact potentials of each impact categories of the polyester TGIC powder coating paint classified by life cycle stages were shown in Tables 16 and 17 for utility databases of Thailand and SimaPro, respectively. For more simplicity, the percentage of environmental impact potentials (characterization value) was constructed, as shown in Figures 16 and 17. From Figure 16, the utility database of Thailand was used. It could be clearly observed that the coating stage gave the highest environmental impact potentials in most impact categories. On the other hand, the transportation and raw materials production stages revealed the highest contributions for ozone layer depletion. From Figure 17, the utility database of SimaPro was used, the highest contributions in all impact categories were effected by 3 stages in life cycle including coating, raw materials production, and transportation. The highest contributions in greenhouse effect, acidification, heavy metals, and solid wastes came from the coating stage, while the raw materials production stage mainly caused summer smog, carcinogens, and energy resources. For ozone layer depletion and eutrophication, most contributions came from the transportation stage.

In Figure 18, environmental impact potentials of all impact categories were grouped into the single score or the total environmental impact. It clearly showed that total environmental impact potentials of the coating phase greatly reduced when the utility database of SimaPro was used. Furthermore, the same trend from both results obtained from utility databases of Thailand and SimaPro were found. The contributions of the total environmental impact of polyester TGIC powder coating paint life cycle were arranged in order from the highest to the lowest as follows: coating > raw materials production > transportation.

From the database of Thailand, it was found that total environmental impact potentials of the coating, the raw materials production, and transportation phases contributed approximately 81%, 12%, and 6% of the total environmental impact in life cycle of polyester TGIC powder coating paint, respectively. The environmental impacts from other phases were rather small when compared with these 3 phases.

From the database of SimaPro, it was found that total environmental impact potentials of the coating, the raw materials production, and transportation phases contributed approximately 42%, 37%, and 20% of the total environmental impact in life cycle of polyester TGIC powder coating paint, respectively. The other phases showed very small impact when compared with these 3 phases.

2.1.2 Hot spot of polyester TGIC powder coating paint life cycle

In order to clarify the hot spot through the life cycle of polyester TGIC powder coating paint, 3 phases of which greatly affected the environmental impact were considered.

Coating phase

Since coating phase from both of utility databases exhibited the most contribution to the environmental impact, so this phase was considered for finding the major hot spot. Moreover, the effect from using two different sources of the utility database was also considered.

The total environmental impact scores of the coating phase calculated using utility databases of Thailand and SimaPro were assessed by Simapro 5.1 with Eco-indicator method and results were presented in Figures 19 and 20, respectively.

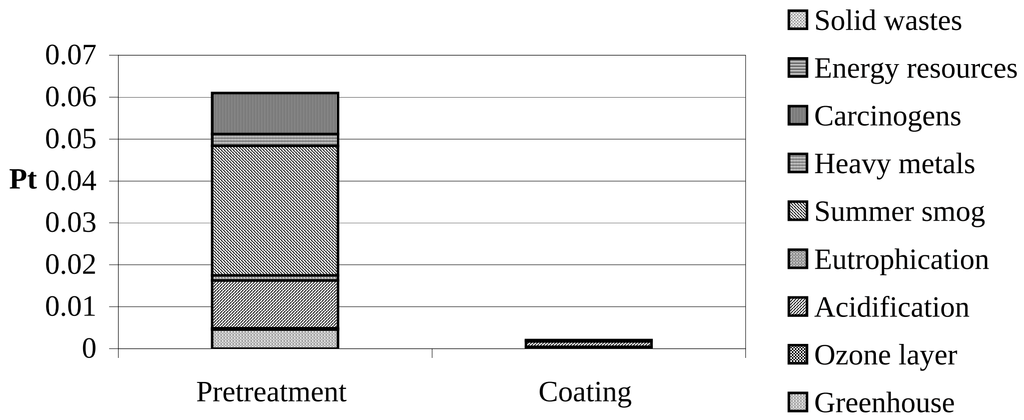


Figure 19 The total environmental impact score of each process in the coating phase of polyester TGIC powder coating paint life cycle calculated using the utility database of Thailand

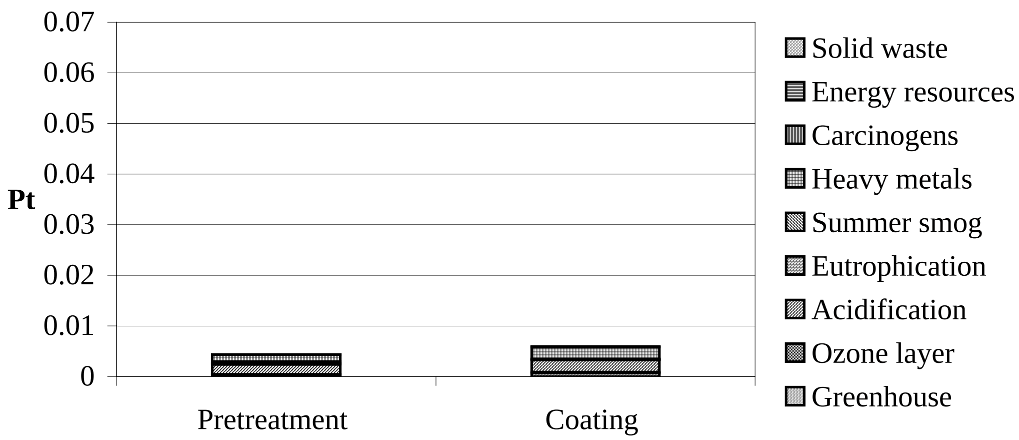


Figure 20 The total environmental impact score of each process in the coating phase of polyester TGIC powder coating paint life cycle calculated using the utility database of SimaPro

The assessment results as shown in Figures 19 and 20 indicated different results between utility databases of Thailand and SimaPro. For polyester TGIC powder coating paint life cycle, the pretreatment process in the coating phase mainly contributed in the environmental impact when the utility database of Thailand was used, while the coating process in the coating phase mainly contributed in the environmental impact when the utility database of SimaPro was used. This was because the environmental impact potentials of water production in Thailand were more than that of the European country (SimaPro database) for approximatly 6,000 times. Therefore, total environmental impact scores of the pretreatment and coating processes obtained using utility databases of Thailand and SimaPro had significant differents (0.061 and 0.0044 Pt for pretreatment process, and 0.002 and 0.006 Pt for coating process, respectively).

As shown in Figure 19, the pretreatment process in the coating phase had the highest environmental impact contribution. The total environmental impact scores of the pretreatment process were 0.061 Pt or contributed approximately 97% of total environmental impact in the coating phase. Therefore, this pretreatment process was concerned for finding the hot spot in this process. The environmental impact in the pretreatment process was evaluated and shown in Figure 21.

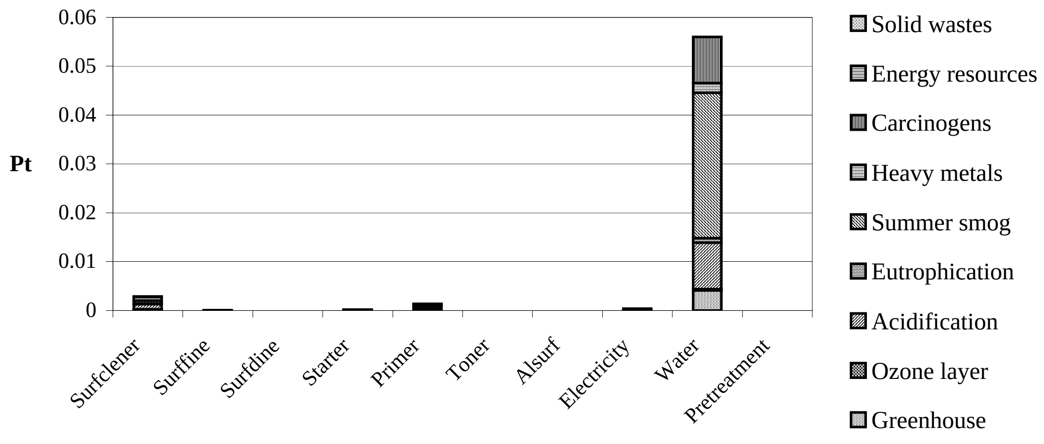


Figure 21 The total environmental impact score of pretreatment process in polyester TGIC powder coating paint life cycle calculated using the utility database of Thailand

As shown in Figure 21, water consumption was the main cause as it generated the highest environmental impact in the pretreatment process. Because the pretreatment process consumed large amounts of water (58 kg of water/1 kg of paint which was coated on workpiece) for cleaning and preparing surface of cabinet as a part of the refrigerator before paint coating, the environmental impact potentials of water consumption in the pretreatment process were 0.056 Pt or contributed approximately 92% of total environmental impact. As a result, the chemical substances used in the pretreatment process including surfcleaner, surffine, surfdine, starter, primer, toner, and alsurf had less impact on the pretreatment process when compared with that of the water consumption.

The most environmental impact of water production in Thailand was caused by iron of which was used as a raw material for building tap water production plant. The total environmental impact potentials of iron production contributed approximately 90% of the total environmental impact of water production. For raw material and chemical substances including water, lime and sodium hydroxide, they had less effect when compared with iron because the iron production consumed a very large energy and resources, especially crude coal that had high environment impact.

For the total environmental impact score of the coating phase obtained using the utility database of SimaPro as shown in Figure 20, it was seen that the coating process in the coating phase had the highest environmental impact contribution. The total environmental impact score of the coating process was 0.006 Pt or contributed approximately 58% of total environmental impact. Main cause of the highest environmental impact in the coating process came from the electricity consumption due to this process use only the electricity for operation.

<u>Raw materials production phase</u>

The environmental impact of raw materials production phase was smaller than the coating phase but higher than the transportation phase in both the utility data sources, as shown in Figure18.

The total environmental impact scores of raw materials production phase calculated using the utility databases of Thailand and SimaPro were assessed by Simapro 5.1 with Eco-indicator method and the results were presented in Figures 22 and 23, respectively.

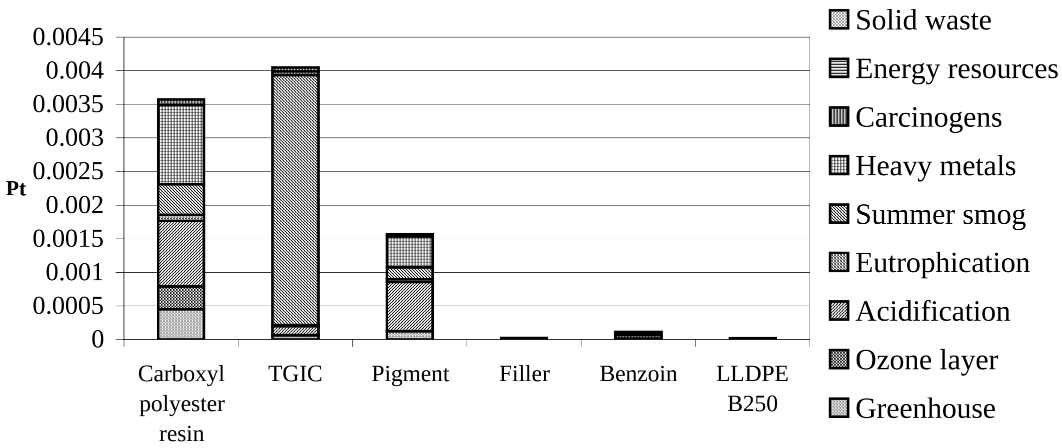


Figure 22 The total environmental impact score of raw materials production phase in polyester TGIC powder coating paint life cycle obtained using the utility database of Thailand

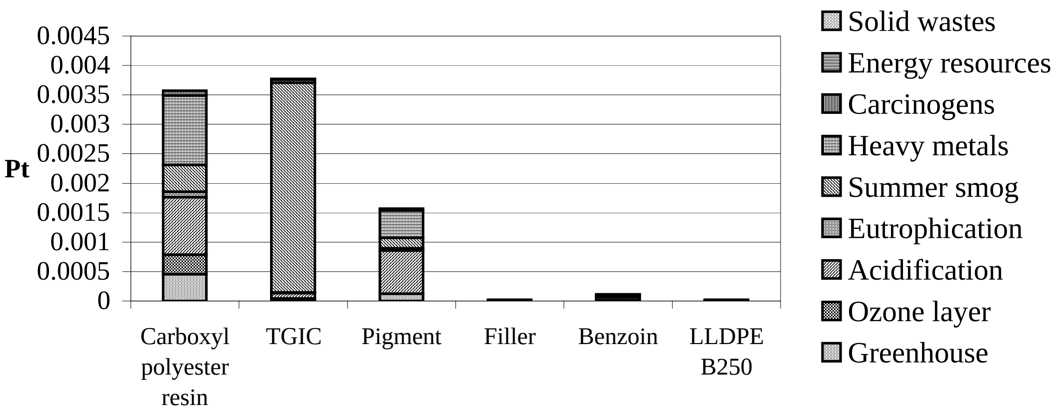


Figure 23 The total environmental impact score of raw materials production phase in polyester TGIC powder coating paint life cycle obtained using the utility database of SimaPro

The assessment results obtained from both utility data sources were quite similar. It was found that triglycidyl isocyanurate (TGIC), carboxyl polyester resin, and pigment had significant effect on the environmental impact. The total environmental impact potentials of TGIC, carboxyl polyester resin, and pigment were 0.0041 Pt, 0.0036 Pt, and 0.0016 Pt or contributed approximately 44%, 39%, and 17% of total environmental impact in raw materials production phase, respectively. Therefore, the productions of triglycidyl isocyanurate, carboxyl polyester resin, and pigment were the main cause, which generated major environmental impact in the raw materials production phase as shown in Figures 22 and 23.

In the case of fillers, benzoin was considered as an additive and linear low density polyethylene (LLDPE) was considered as a packaging material. However, both of them had less effect than TGIC, even the amount of filler used was more than that of TGIC.

Transportation phase

The entire transportation phase was considered in this transportation phase in life cycle of polyester TGIC powder coating paint. These included transportation of raw materials, powder coating paint, workpiece coated by paint, and waste from production processes to the user and disposal site. Since these were no utility used in this phase, therefore only one set of database was used. The environmental impact of transportation phase was evaluated and the result was shown as in Figure 24.

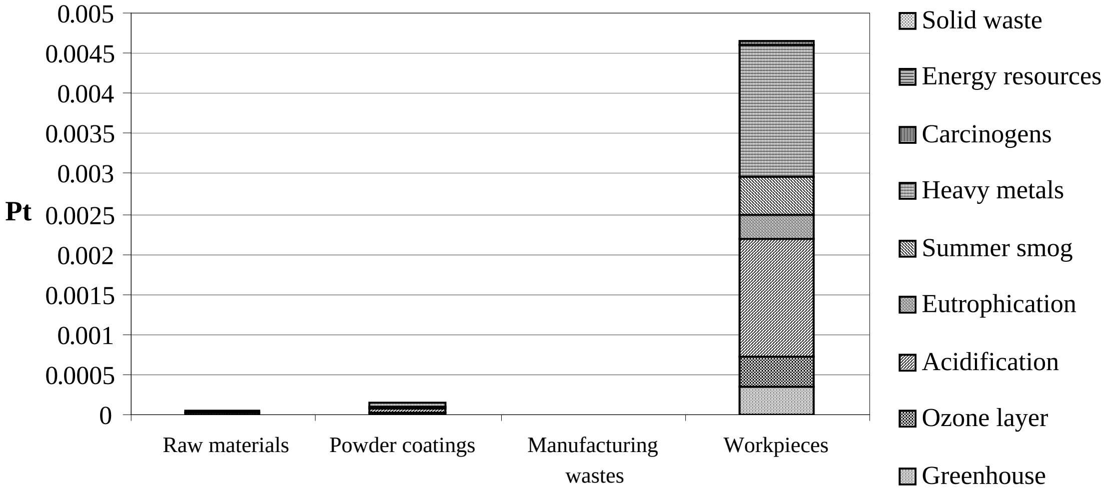


Figure 24 The environmental impact of each transportation section in transportation phase of polyester TGIC powder coating paint life cycle obtained from SimaPro 5.1 with Eco-indicator 95 method

Figure 24 showed the environmental impact of each transportation section in the transportation phase. It obviously indicated that transportation of paint-coated workpiece (cabinet) had the highest environmental impact in transportation stage. This was because the environmental impact of transportation was calculated from type of vehicle, weight, and distance of transportation. Cabinet as a part of refrigerator was made from iron, which its weight was 5.43 kg. The weight of paint-coated workpiece was quite heavier than the transportation in other sections and the distance of workpiece transportation was also farther than others. As a result, the environmental impact of workpiece transportation was 0.0047 Pt or contributed approximately 96% of total environmental impact in the transportation phase.

2.2 Life cycle impact assessment of polyester-epoxy powder coating paint

The results of assessing the environmental impact in the entire life cycle of 1 kg polyester-epoxy powder coating paint were shown in Table 19.

Table 19 The environmental impact potentials of the entire life cycle of 1 kg polyester-epoxy powder coating paints obtained from two different sources of utility database

Impact category	Characterized value		Unit
	Utility database of Thailand	Utility database of SimaPro	
Greenhouse effect	31.2	10.2	kg CO_2-eq
Ozone layer depletion	8.01×10^{-6}	7.85×10^{-6}	kg CFC-11-eq
Acidification	0.182	0.0867	kg SO_2-eq
Eutrophication	0.0147	0.00645	kg PO_4-eq
Summer smog	0.233	0.0113	kg C_2H_4-eq
Heavy metals	6.31×10^{-5}	7.29×10^{-5}	kg Pb-eq
Carcinogens	1.09×10^{-5}	2.98×10^{-7}	kg B(a)P-eq
Energy resources	1440	212	MJ LHV-eq
Solid wastes	13.0	0.453	kg-eq

From Table 19, the environmental impact scores of polyester-epoxy coating paint were quite similar to those of polyester TGIC powder as shown in Table 16. This was because raw materials used in the polyester-epoxy powder coating paint process were similar to those of polyester TGIC powder coating paint, except that of the hardener. In this process, epoxy resin was used as the hardener. Moreover, it was also found that the environmental impact of polyester-epoxy powder coating calculated using the utility database of SimaPro was less than that of the utility database of Thailand in all impact categories. This was because the impacts of the electricity and water generation of foreign countries (Europe) as used in polyester-epoxy powder coating was quite less than that of the electricity and water generation of Thailand.

2.2.1 Impact assessment of each phase

The impact assessment of the whole life cycle could be applied by considering all unit processes including raw materials production, powder coating manufacturing, coating, use paint coated on workpiece, disposal, and transportation. The assessment results showed the environment impact of each phase and indicated a phase of which generated the highest environmental impact potentials.

The environmental impact potentials of each phase in the whole life cycle of polyester-epoxy powder coating paints obtained from the use of two different sources of utility database were summarized in Tables 20 and 21. Similarly, the graphical overviews of environmental impact potentials (characterization value) constructed using two different sources of utility database were presented in Figures 25 and 26. The graphical overview of total environmental impact scores was presented in Figure 27.

Table 20 Environmental impact of each phase in the whole life cycle of 1 kg polyester-epoxy powder coating paint calculated from the utility database of Thailand

Impact categories / Phases	Greenhouse effect ($kg\ CO_2$-eq)	Ozone layer depletion (kg CFC11-eq)	Acidification ($kg\ SO_2$-eq)	Eutrophication ($kg\ PO_4$-eq)	Summer smog ($kg\ C_2H_4$-eq)	Heavy metals (kg Pb-eq)	Carcinogens (kg B(a)P*-eq)	Energy resources (MJ)	Solid wastes (kg)
Raw materials production	2.42	1.65×10^{-6}	0.0198	0.00151	0.00433	1.26×10^{-5}	8.72×10^{-8}	110	0.22
Manufacturing	0.344	6.62×10^{-8}	0.00224	0.000183	0.0028	6.77×10^{-7}	1.33×10^{-7}	18.1	0.156
Coating	26.5	2.76×10^{-6}	0.143	0.0105	0.222	3.14×10^{-5}	1.06×10^{-5}	1280	12.6
Use	-	-	-	-	-	-	-	-	-
Disposal	0.00455	4.81×10^{-10}	1.16×10^{-5}	6.29×10^{-6}	4.24×10^{-7}	3.28×10^{-8}	3.33×10^{-11}	0.0197	0
Transportation	1.93	3.53×10^{-6}	0.0173	0.0025	0.00345	1.84×10^{-5}	7.83×10^{-8}	27.4	0
Total	31.2	8.01×10^{-6}	0.182	0.0147	0.233	6.31×10^{-5}	1.09×10^{-5}	1440	13

(* Benzo [a] Pyrene- it applied in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbons)

Table 21 Environmental impact of each phase in the whole life cycle of 1 kg polyester-epoxy powder coating paint calculated from the utility database of SimaPro

Impact categories / Phases	Greenhouse effect ($kg\ CO_2$-eq)	Ozone layer depletion (kg CFC11-eq)	Acidification ($kg\ SO_2$-eq)	Eutrophication ($kg\ PO_4$-eq)	Summer smog ($kg\ C_2H_4$-eq)	Heavy metals (kg Pb-eq)	Carcinogens (kg B(a)P*-eq)	Energy resources (MJ)	Solid wastes (kg)
Raw materials production	2.42	1.65×10^{-6}	0.0198	0.00151	0.00433	1.26×10^{-5}	8.72×10^{-8}	110	0.22
Manufacturing	0.112	1.06×10^{-7}	0.00133	6.76×10^{-5}	7.38×10^{-5}	1.36×10^{-6}	4.10×10^{-9}	2.27	5.81×10^{-5}
Coating	5.76	2.56×10^{-6}	0.0483	0.00237	0.00343	4.05×10^{-5}	1.29×10^{-7}	72.1	0.232
Use	-	-	-	-	-	-	-	-	-
Disposal	0.00455	4.81×10^{-10}	1.16×10^{-5}	6.29×10^{-6}	4.24×10^{-7}	3.28×10^{-8}	3.33×10^{-11}	0.0197	0
Transportation	1.93	3.53×10^{-6}	0.0173	0.0025	0.00345	1.84×10^{-5}	7.83×10^{-8}	27.4	0
Total	10.2	7.85×10^{-6}	0.0867	0.00645	0.0113	7.29×10^{-5}	2.98×10^{-7}	212	0.453

(* Benzo [a] Pyrene- it applied in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbons)

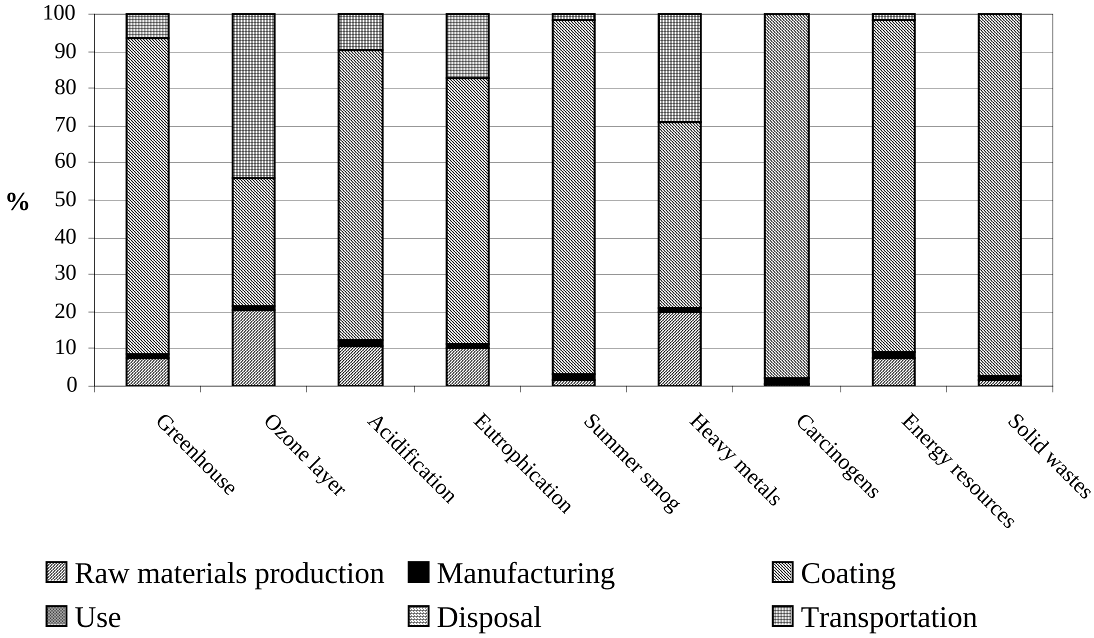


Figure 25 Contribution of the characterization value of each impact categories of each phase in polyester-epoxy powder coating paint life cycle obtained from the utility database of Thailand

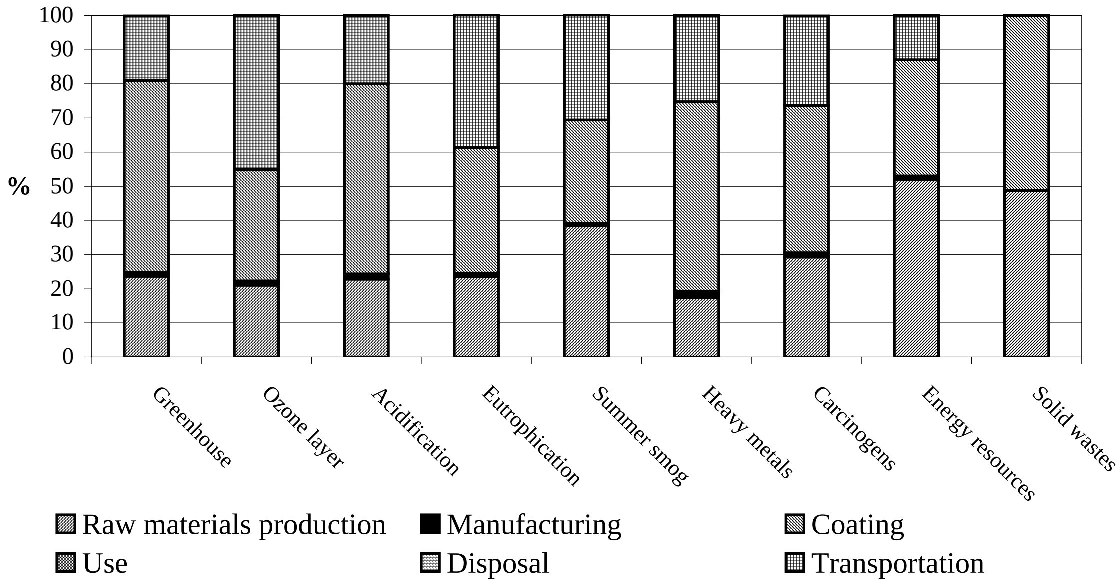


Figure 26 Contribution of the characterization value of each impact categories of each phase in polyester-epoxy powder coating paint life cycle obtained from the utility database of SimaPro

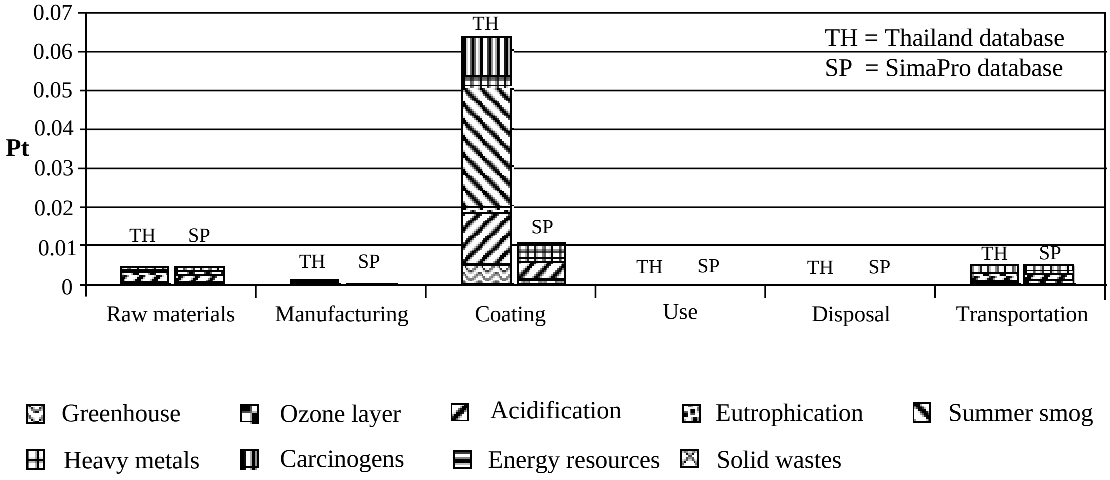


Figure 27 The total environmental impact scores of each phase in polyester-epoxy powder coating paint life cycle obtained from utility databases of Thailand and SimaPro

The environmental impact potentials of each impact categories of polyester-epoxy powder coating paint classified by life cycle stages were shown in Tables 20 and 21 for utility databases of Thailand and SimaPro, respectively. For more simplicity, the percentage of environmental impact potentials (characterization value) was constructed, as shown in Figures 25 and 26. From Figure 25, the utility database of Thailand was used. It could be clearly observed that the coating stage gave the highest environmental impact potentials in most impact categories. On the other hand, the transportation stage revealed the highest contributions for ozone layer depletion. From Figure 26, the utility database of SimaPro was used, the highest contributions in all impact categories were effected by 3 stages in life cycle including coating, raw materials production, and transportation. The highest contributions in greenhouse effect, acidification, heavy metals, carcinogens, and solid wastes came from the coating stage, while raw materials production stage mainly caused summer smog and energy resources. For ozone layer depletion and eutrophication, most contributions came from the transportation stage.

In Figure 27, environmental impact potentials of all impact categories were grouped into the single score or the total environmental impact. It clearly showed that total environmental impact potentials of the coating phase greatly reduced when the utility database of SimaPro was used. Furthermore, the same trend from both results obtained from the utility databases of Thailand and SimaPro were found. The contributions of the total environmental impact of polyester-epoxy powder coating paint life cycle were arranged in order from the highest to the lowest as follows: coating > transportation > raw materials production.

From the database of Thailand, it was found that total environmental impact potentials of coating, transportation, and raw materials production phases contributed approximately 86%, 7%, and 6% of the total environmental impact in life cycle of polyester-epoxy powder coating paint, respectively. The environmental impacts from other phases were rather small when compared with these 3 phases.

From the database of SimaPro, it was found that total environmental impact potentials of coating, transportation, and raw materials production phases contributed approximately 52%, 24%, and 22% of total environmental impact in life cycle of polyester-epoxy powder coating paint, respectively. The other phases showed very small impact when compared with these 3 phases.

2.2.2 Hot spot of polyester-epoxy powder coating paint life cycle

In order to clarify the hot spot through the life cycle of polyester-epoxy powder coating, 3 phases of which greatly affected the environmental impact were considered. Hot spot of coating phase and transportation phase in polyester-epoxy powder coating paint were similar to that of the polyester TGIC powder coating paint because life cycle of polyester-epoxy powder coatings was quite similar to life cycle of polyester TGIC powder coatings except the quantity of raw materials used and type of hardener.

Water consumption was main factor as it generated the highest environmental impact in the coating phase when the utility database of Thailand was used. On the other hand, electricity consumption was main factor when the utility database of SimaPro was used. In the transportation phase, the transportation of paint-coated workpiece was the main factor that generated the highest environmental impact. However, the hot spot of raw materials production was still different from polyester TGIC powder coating paint as described below.

Raw materials production phase

The total environmental impact scores of raw materials production phase calculated using the utility databases of Thailand and SimaPro were assessed by Simapro 5.1 with Eco-indicator method and the results were presented in Figures 28 and 29, respectively.

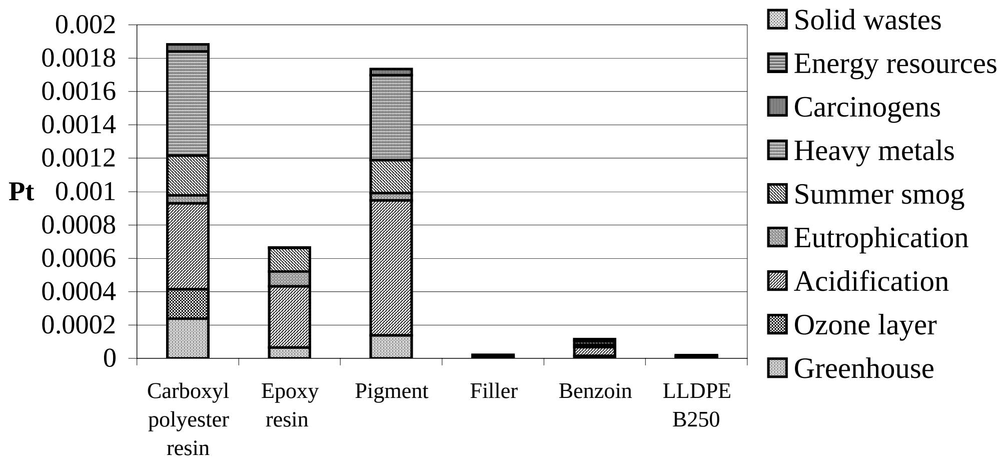


Figure 28 The total environmental impact score of raw materials production phase in polyester-epoxy powder coating paint life cycle obtained using the utility database of Thailand

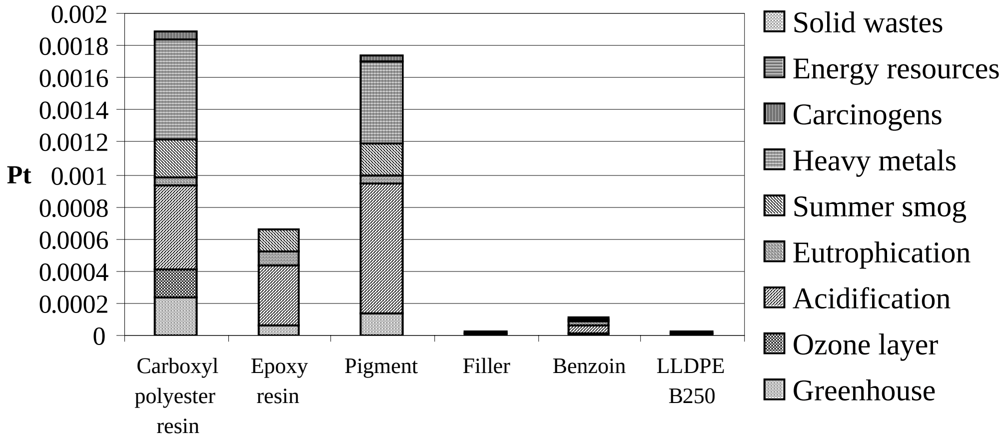


Figure 29 The total environmental impact score of raw materials production phase in polyester-epoxy powder coating paint life cycle obtained using the utility database of SimaPro

The assessment results obtained from both utility data sources were quite similar. It was found that carboxyl polyester resin, pigment, and epoxy resin had significant effect on the environmental impact. The total environmental impact potentials of carboxyl polyester resin, pigment, and epoxy resin were 0.0019 Pt, 0.0017 Pt, and 0.0007 Pt or contributed approximately 42%, 39%, and 15% of total environmental impact in raw materials production phase, respectively. Therefore, the productions of carboxyl polyester resin, pigment, and epoxy resin were the main cause, which generated major environmental impact in the raw materials production phase as shown in Figures 28 and 29.

In the case of fillers, benzoin was considered as an additive and linear low density polyethylene (LLDPE) was considered as a packaging material. However, both of them had less effect.

2.3 Life cycle impact assessment of solvent-based paint

The assessment of the environmental impact in the entire life cycle of 1 kg solvent-based paint was undertaken by using SimaPro 5.1 with Eco-indicator 95 method, covering the production of raw materials, manufacturing, coating, use, disposal, and transportation. It was found that the entire life cycle of 1 kg solvent-based paint contributed the environmental impact as shown in Table 22.

Table 22 The environmental impact potentials of the entire life cycle of 1 kg solvent -based paints obtained from two different sources of utility database

Impact category	Characterized value		Unit
	Utility database of Thailand	Utility database of SimaPro	
Greenhouse effect	190	27.2	kg CO_2-eq
Ozone layer depletion	2.44×10^{-5}	1.62×10^{-5}	kg CFC-11-eq
Acidification	0.974	0.205	kg SO_2-eq
Eutrophication	0.102	0.042	kg PO_4-eq
Summer smog	1.70	0.0225	kg C_2H_4-eq
Heavy metals	0.000354	0.000334	kg Pb-eq
Carcinogens	8.11×10^{-5}	6.81×10^{-7}	kg B(a)P-eq
Energy resources	9550	369	MJ LHV-eq
Solid wastes	95.7	0.864	kg-eq

From Table 22, it was found that the environmental impact of the solvent-based paint used the utility database of SimaPro was less than that obtained from the utility database of Thailand in all impact categories. This was because the impacts of the electricity and water generation of foreign countries (Europe) as used in solvent-based paint was quite less than that of the electricity and water generation of Thailand.

2.3.1 Impact assessment of each phase

All the processes in the life cycle of solvent-based paint including raw materials production, manufacturing, coating, use, disposal, and transportation were evaluated for quantifying the stage which generated the highest environmental impact potentials.

The environmental impact potentials of each phase in the whole life cycle of solvent-based paint obtained from the use of two different sources of utility database were summarized in Tables 23 and 24. Similarly, the graphical overviews of environmental impact potentials (characterization value) constructed using two different sources of utility database were presented in Figures 30 and 31. The graphical overview of total environmental impact scores was presented in Figure 32.

Table 23 Environmental impacts of each phase in the whole life cycle of 1 kg solvent-based paint calculated from the utility database of Thailand

Impact category / Phases	Greenhouse effect (kg CO_2-eq)	Ozone layer depletion (kg CFC11-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO_4-eq)	Summer smog (kg C_2H_4-eq)	Heavy metals (kg Pb-eq)	Carcinogens (kg B(a)P*-eq)	Energy resources (MJ)	Solid wastes (kg)
Raw materials production	2.23	1.65×10^{-6}	0.0178	0.00133	0.0114	1.66×10^{-5}	9.20×10^{-8}	67.1	0.404
Manufacturing	2.61	4.30×10^{-8}	0.0149	0.00153	0.00134	2.42×10^{-6}	4.81×10^{-8}	73.1	0.142
Coating	184	1.92×10^{-5}	0.924	0.0964	1.68	3.17×10^{-4}	8.08×10^{-5}	9380	95.2
Use	-	-	-	-	-	-	-	-	-
Disposal	9.65×10^{-4}	1.02×10^{-10}	2.46×10^{-6}	1.33×10^{-6}	8.98×10^{-8}	6.95×10^{-9}	7.06×10^{-12}	0.00417	0
Transportation	1.92	3.51×10^{-6}	0.017	0.00247	0.00343	1.83×10^{-5}	7.78×10^{-8}	27.3	0
Total	190	2.44×10^{-5}	0.974	0.102	1.7	3.54×10^{-4}	8.11×10^{-5}	9550	95.7

(* Benzo [a] Pyrene- it applied in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbons)

Table 24 Environmental impacts of each phase in the whole life cycle of 1 kg solvent-based paint calculated from the utility database of SimaPro

Impact category / Phases	Greenhouse effect (kg CO_2-eq)	Ozone layer depletion (kg CFC11-eq)	Acidification (kg SO_2-eq)	Eutrophication (kg PO_4-eq)	Summer smog (kg C_2H_4-eq)	Heavy metals (kg Pb-eq)	Carcinogens (kg B(a)P*-eq)	Energy resources (MJ)	Solid wastes (kg)
Raw materials production	2.23	1.65×10^{-6}	0.0178	0.00133	0.0114	1.66×10^{-5}	9.20×10^{-8}	67.1	0.404
Manufacturing	3.68	1.78×10^{-6}	0.0258	9.22×10^{-4}	8.88×10^{-4}	2.61×10^{-5}	8.09×10^{-8}	42.5	0.0864
Coating	19.4	9.27×10^{-6}	0.145	0.0372	0.00686	2.73×10^{-4}	4.30×10^{-7}	232	0.374
Use	-	-	-	-	-	-	-	-	-
Disposal	9.65×10^{-4}	1.02×10^{-10}	2.46×10^{-6}	1.33×10^{-6}	8.98×10^{-8}	6.95×10^{-9}	7.06×10^{-12}	0.00417	0
Transportation	1.92	3.51×10^{-6}	0.017	0.00247	0.00343	1.83×10^{-5}	7.78×10^{-8}	27.3	0
Total	27.2	1.62×10^{-5}	0.205	0.042	0.0225	3.34×10^{-4}	6.81×10^{-7}	369	0.864

(* Benzo [a] Pyrene- it applied in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbons)

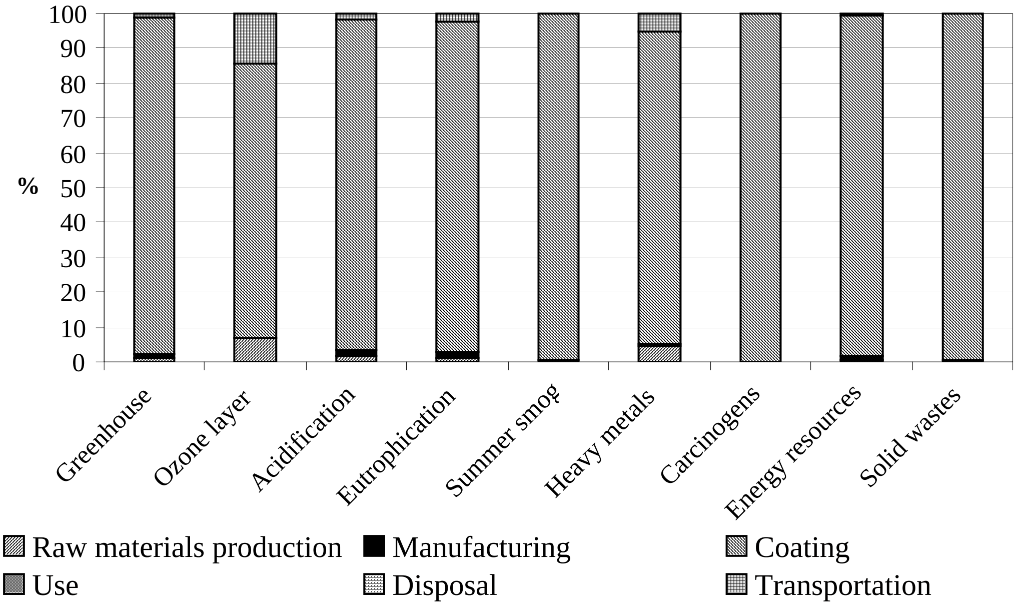


Figure 30 Contribution of the characterization value of each impact categories of each phase in solvent-based paint life cycle obtained from the utility database of Thailand

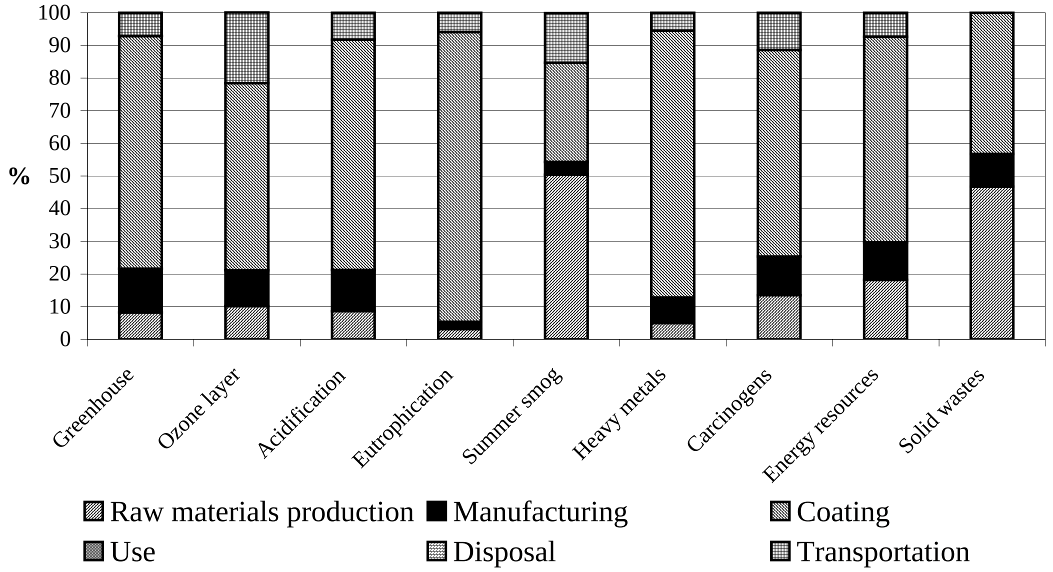


Figure 31 Contribution of the characterization value of each impact categories of each phase in solvent-based paint life cycle obtained from the utility database of SimaPro

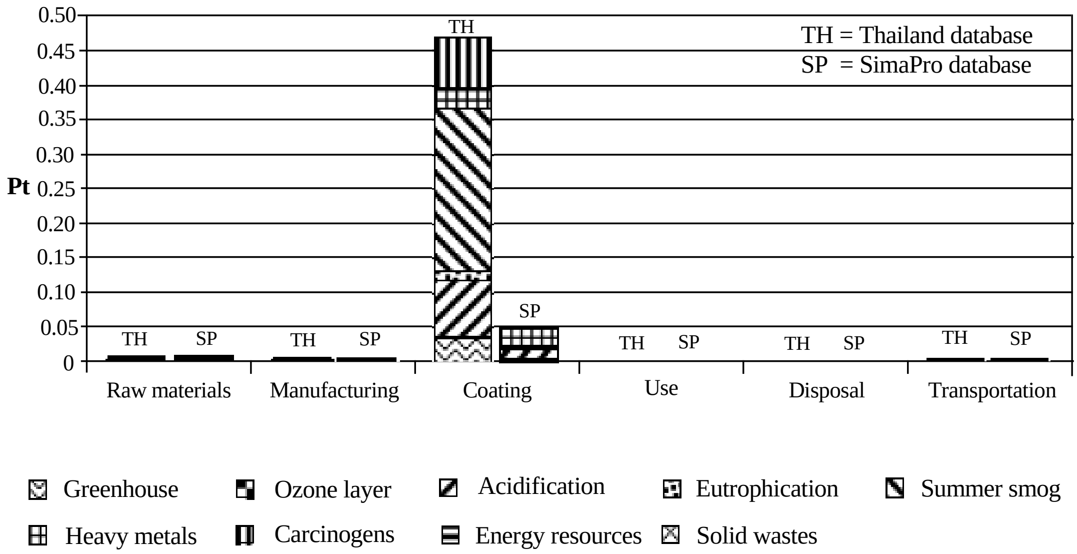


Figure 32 The total environmental impact scores of each phase in solvent-based paint life cycle obtained from the utility databases of Thailand and SimaPro

The environmental impact potentials of each impact categories of the solvent-based paint classified by life cycle stages were shown in Tables 23 and 24 for utility databases of Thailand and SimaPro, respectively. For more simplicity, the percentage of environmental impact potentials (characterization value) was constructed, as shown in Figures 30 and 31. From Figure 30, the utility database of Thailand was used. It could be clearly observed that the coating stage gave the highest environmental impact potentials in all impact categories. For Figure 31, the utility database of SimaPro was used. It showed that the highest contributions in all impact categories were effected by 4 stages in life cycle including coating, manufacturing, raw materials production, and transportation. The highest contributions in greenhouse effect, ozone layer depletion, acidification, eutrophication, heavy metals, carcinogens, and energy resources mainly came from the coating stage while raw materials production stage mainly caused summer smog and solid wastes.

In Figure 32, environmental impact potentials of all impact categories were grouped into the single score or the total environmental impact. It clearly showed that the total environmental impact potentials of coating phase reduced very much when the utility database of SimaPro was used. Furthermore, the same trend from both the results obtained from the utility databases of Thailand and SimaPro were observed. The highest contribution of the total environmental impact of the solvent-based paint life cycle came from the coating phase. It was found that the total environmental impact potentials of the coating phase contributed approximately 97% and 75% of total environmental impact in the life cycle of solvent-based paint for the utility databases of Thailand and SimaPro, respectively. The other phases showed very small environmental impact when compared with coating phase.

2.3.2 Hot spot(s) of solvent-based paint life cycle

In order to clarify the hot spot through the life cycle of solvent-based paint, coating phase of which greatly affected the environmental impact was considered.

Coating phase

Since coating phase from both of utility databases exhibited the most contribution to the environmental impact, so this phase was considered for finding the major hot spot. Moreover, the effect from using two different sources of utility database was also considered.

The total environmental impact scores of coating phase calculated using the utility databases of Thailand and SimaPro were assessed by Simapro 5.1 with Eco-indicator method and the results were presented in Figures 33 and 34, respectively.

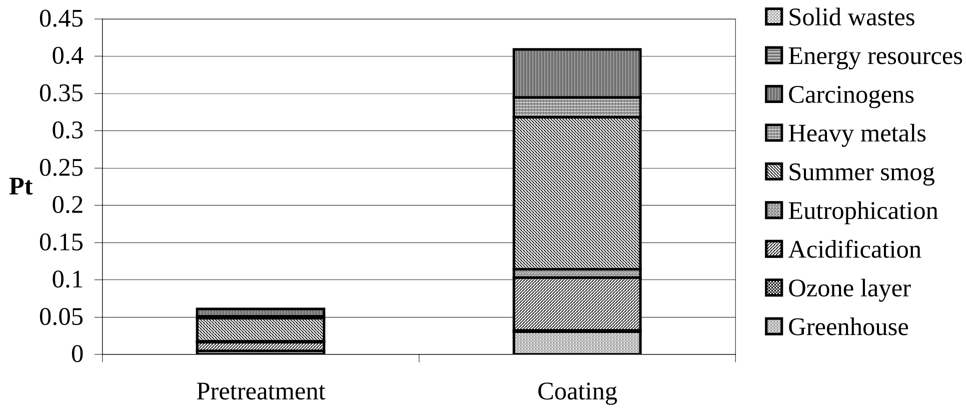


Figure 33 The total environmental impact scores of each process in the coating phase of solvent-based paint life cycle calculated using the utility database of Thailand

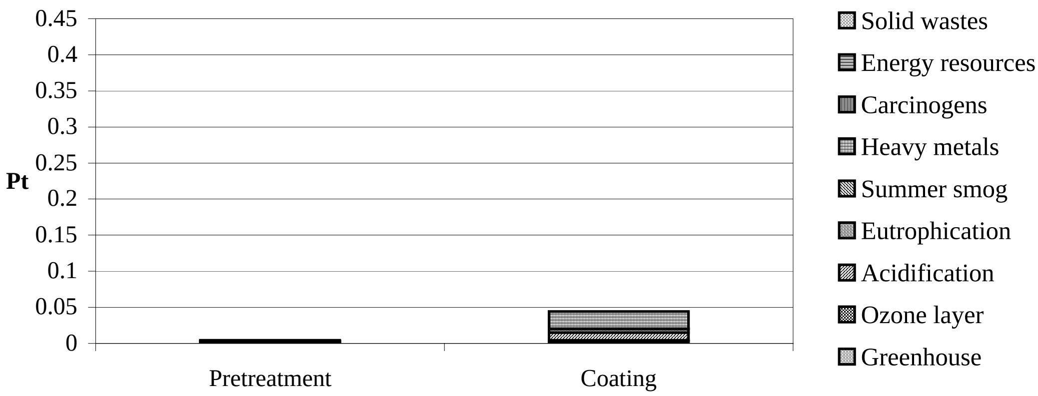


Figure 34 The total environmental impact scores of each process in the coating phase of solvent-based paint life cycle calculated using the utility database of SimaPro

The assessment results obtained from both utility data sources were quite similar. The coating process in the coating phase revealed the highest environmental impact contribution. The total environmental impact potentials of the coating process were 0.41 Pt and 0.044 Pt or contributed approximately 87% and 91% of the total environmental impact in the coating phase for the utility databases of Thailand and

SimaPro, respectively. Therefore, the coating process was concerned for finding the key factor that generated major environmental impact. The environmental impact in the pretreatment process was evaluated and shown in Figures 35 and 36 for the utility databases of Thailand and SimaPro, respectively.

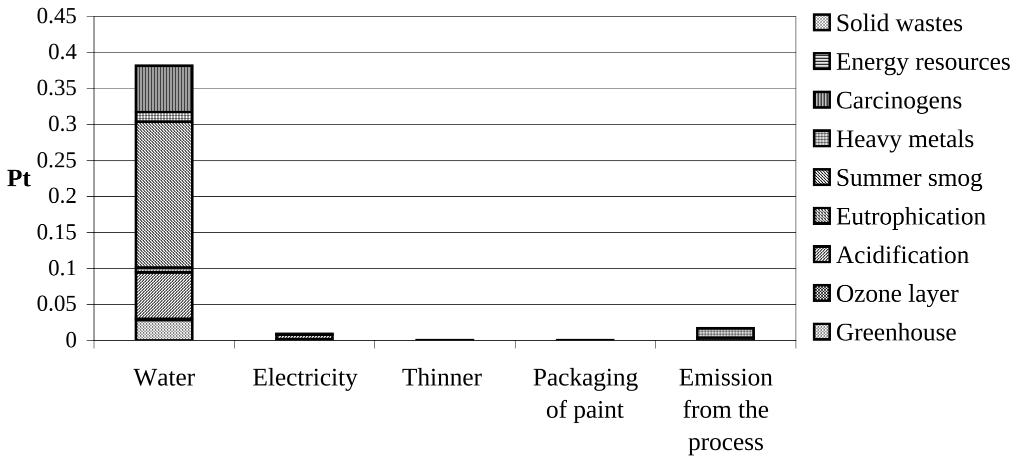


Figure 35 The total environmental impact score of coating process in solvent-based paint life cycle calculated using the utility database of Thailand

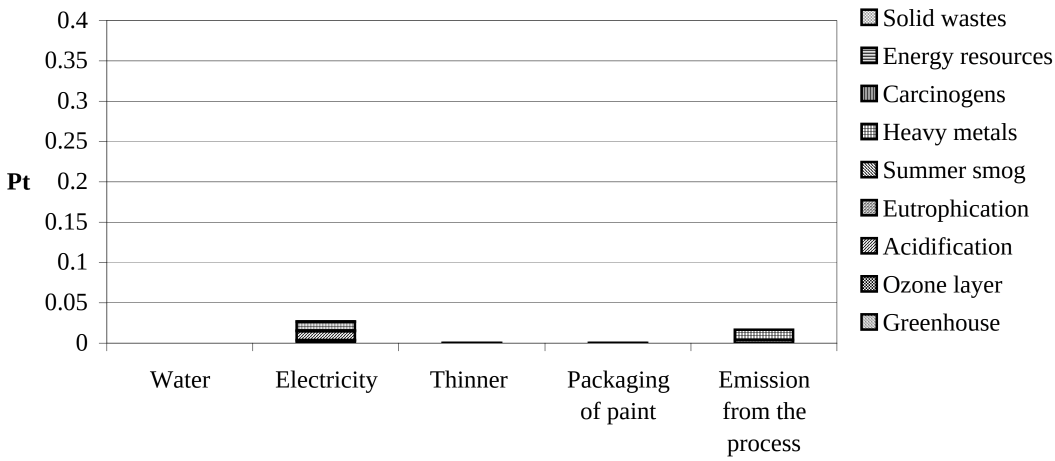


Figure 36 The total environmental impact score of coating process in solvent-based paint life cycle calculated using the utility database of SimaPro

As shown in Figure 35, water consumption was the main cause as it generated the highest environmental impact in the coating process. Because the coating process consumed large amounts of water (396 kg of water/1 kg of paint which was coated on workpiece) for trapping the overspray paints and volatile organic compounds during spray-coating paints on a workpiece in the paint booth, the environmental impact potentials of water consumption in the coating process were 0.382 Pt or contributed approximately 93% of total environmental impact. As a result, the emission during coating paint, electricity, thinner, and packaging of paint had less impact on the coating process when compared with that of the water consumption.

For the total environmental impact score of the coating process obtained using the utility database of SimaPro as shown in Figure 36, it was seen that the electricity consumption and emission in the coating process had the highest environmental impact contribution. The total environmental impact score of the electricity consumption and emission from the coating process were 0.027 Pt and 0.017 Pt or contributed approximately 60% and 38% of total environmental impact. Major emission that generated the highest environmental impact in the coating process came from heavy metals dissolved in the wastewater from the overspray paints and volatile organic compounds trap.

The total environmental impact score of the water consumption in the coating process was very small when the utility database of SimaPro was used due to the environmental impact potentials of water production of the European country (as a SimaPro database) had less impact. As a result, environmental impact of the electricity consumption in the coating process was increased because the environmental impact potentials of the electricity production in the European country had higher than that of Thailand for approximately 3 times.

2.4 Comparison of environmental impact potentials of 3 types of paint

The comparison of the environmental impact in the entire life cycle of three types of paints was undertaken by using SimaPro 5.1 with Eco-indicator 95 method. The quantity of paint applied to 1 m^2 of workpiece was set as the functional unit for comparing the environmental impact. The quantities of powder coating paint and solvent-based paint applied to 1 m^2 of workpiece were 120.99 g and 228.21 g, respectively.

The comparison of the environmental impact potentials through the life cycle of three types of paint obtained from the use of two different sources of utility databases was indicated in Figure 37.

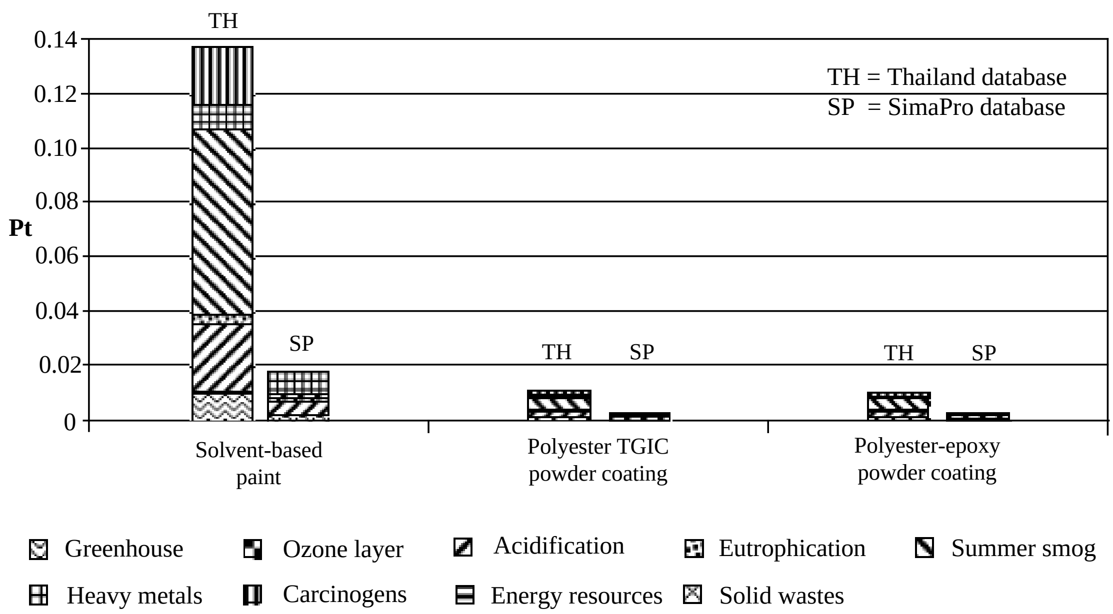


Figure 37 Comparison of environmental impact potentials of each life cycle of paints obtained from utility databases of Thailand and SimaPro

In Figure 37, the same trend of results obtained from utility databases of Thailand and SimaPro was observed. The solvent-based paint had higher environmental impact than those of polyester TGIC and polyester-epoxy powder coating paints, respectively. Because the impacts of the water generation of Thailand was greater than that of the European countries, therefore, the total environmental impact score calculated using the utility database of Thailand was higher than that of the SimaPro.

Comparing between LCA of polyester TGIC powder coating and LCA of polyester-epoxy powder coating, it was found that the environmental impact of polyester-epoxy powder coating paint was less than that of polyester TGIC powder coating paint. This was because the toxicity of the hardener (epoxy resin) used in polyester-epoxy powder coating was quite less than that of the hardener (triglycidyl isocyanurate) used in polyester TGIC powder coating paint.

In the life cycle of three types of paints calculated using the utility database of Thailand, impact categories including summer smog, acidification, and carcinogens revealed the largest environmental impact score. The cause of summer smog, acidification, and carcinogens production came from the iron which was used as raw materials for the construction of tap water production plant, then the water consumption was the hot spot in the life cycle of three types of paints. The iron production consumed very large energy and resources, especially crude coal which it had high significant effect on the environment.

For life cycle of polyester TGIC powder coating paint calculated using the utility database of SimaPro, impact categories including acidification, heavy metals, and summer smog revealed the largest environmental impact score. The main cause of acidification production came from the truck which was used for the entire transportation. However, for the carboxyl polyester resin and TGIC productions, heavy metals and summer smog were produced, respectively.

In the life cycle of polyester-epoxy powder coating paint obtained using the utility database of SimaPro, impact categories including acidification and heavy metals revealed the largest environmental impact score. The main cause of acidification production came from the production of sodium hydroxide of which used as the pretreatment substances; and truck used in the entire transportation, while the entire transportation by truck and titanium dioxide production were the main factors of heavy metals generation.

Impact categories including heavy metals and acidification revealed the largest environmental impact score in the life cycle of solvent-based paint of which used the utility database of SimaPro. The heavy metals production was caused by the emission to water of paint in the coating process, while the acidification was caused by the electricity generation and sodium hydroxide production.

3. Improvements and Suggestion

In this part, the option for reducing the environmental impacts of three types of paints used the utility database of Thailand was only proposed.

3.1 Powder coating paint

From the previous section, it can be concluded that the environmental impacts of powder coating paints including polyester TGIC and polyester-epoxy powder coating paints were extremely high in the pretreatment process. Moreover from the impact assessment, the large amount of water consumption in the pretreatment process contributed to major environmental impact potentials. Therefore, this modification was focused on water use in the pretreatment process of which considered as the key factor in this research.

From the case study of Hoffman Engineering Company in Minnesota, USA, the amount of water consumption could be reduced up to 50% in the pretreatment process when the modification in the pretreatment process including chemical cleaning, rinsing, phosphate conversion coating, and final seal processes were applied by the installation of water-saving equipment. The shut-off valve, pressure gauge, control valve, inductive conductivity meter, and automated conductivity meter are the water-saving devices which can be installed to reduce the overflow of usable water and prevent the unintended open valve.

The new pretreatment process have been proposed to use in the pretreatment process of Sanyo Universal Electric Public Company Limited (SUE) and it was assumed that 50% of amount of water use could be reduced because the pretreatment process of SUE and Hoffman Engineering Company was quite similar. However, the environmental impact potentials from the water-saving devices installation in the new pretreatment process were excluded. As a result, the comparison of environmental impact potentials between 2 pretreatment processes can be summarized as shown in Table 25.

Table 25 The comparison of environmental impact potentials between the present and the proposed pretreatment processes

Impact category	Present pretreatment process	Proposed pretreatment process	Unit
Greenhouse effect	24	13.2	kg CO_2
Ozone layer depletion	2.76×10^{-6}	1.57×10^{-6}	kg CFC11
Acidification	0.128	0.0751	kg SO_2
Eutrophication	0.00895	0.00537	kg PO_4
Summer smog	0.222	0.115	kg C_2H_4
Heavy metals	3.12×10^{-5}	2.07×10^{-5}	kg Pb
Carcinogens	1.06×10^{-5}	5.44×10^{-6}	kg B(a)P
Energy resources	1220	641	MJ LHV
Solid wastes	12.6	6.54	kg

From Table 25, it was clearly seen that the environmental impact potentials of the proposed pretreatment process was greatly reduced in all impact categories which were approximately decreased 34%-50% of the environmental impact potentials of the present pretreatment process.

The total environmental impact scores of the entire life cycle of polyester TGIC and polyester-epoxy powder coating used the proposed pretreatment process were evaluated and compared with those of the powder coating including polyester TGIC and polyester-epoxy powder coating used the present pretreatment process as shown in Figures 38 and 39, respectively.

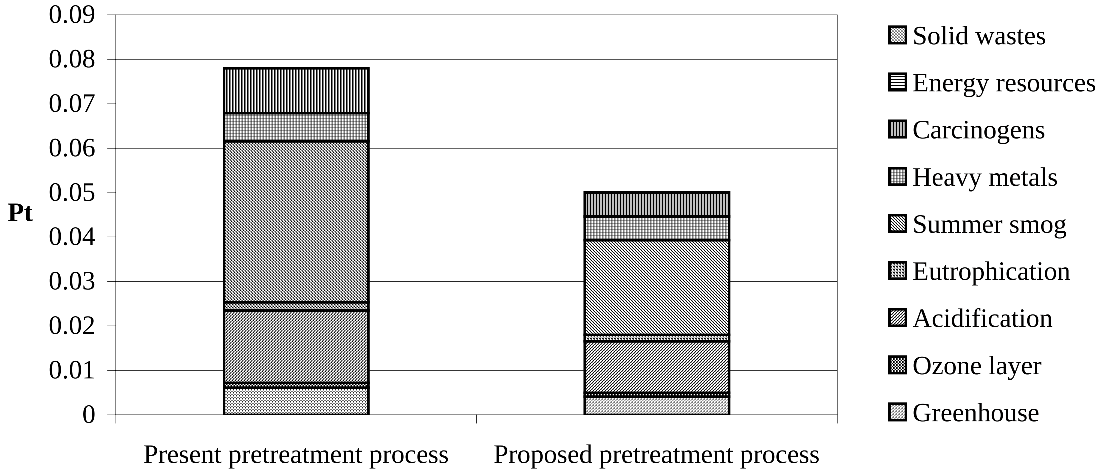


Figure 38 Comparing environmental impacts of the entire life cycle of polyester TGIC powder coatings that used the proposed pretreatment process instead of the present pretreatment process

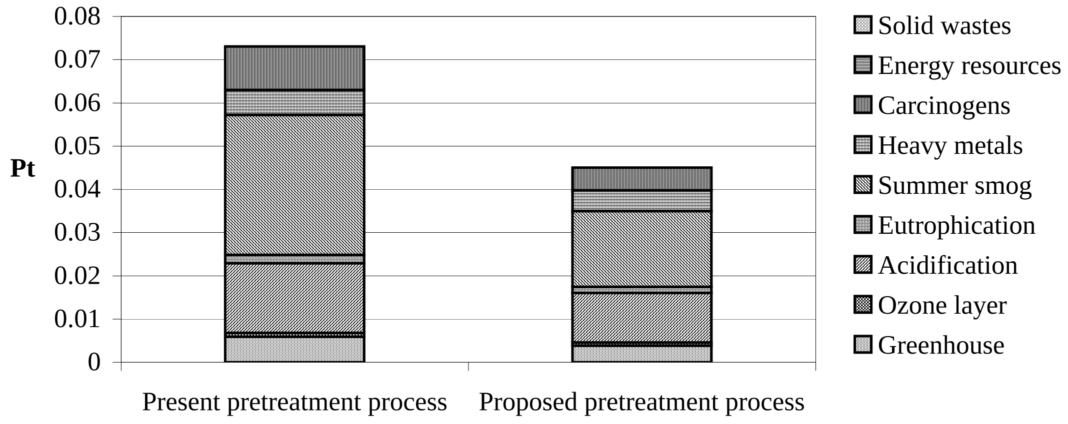


Figure 39 Comparing environmental impacts of the entire life cycle of polyester-epoxy powder coatings that used the proposed pretreatment process instead of the present pretreatment process

From Figures 38 and 39, the results indicated that the total environmental impact potentials of the entire life cycle of polyester and polyester-epoxy powder coating from the proposed pretreatment process was reduced up to 36% and 38%, respectively.

The reduction of impact potentials in the pretreatment process resulting from the proposed improvement is significantly high, of which makes this improvement become interestingly and practically.

3.2 Solvent-based paint

From the impact assessment result, it was found that solvent-based paint coating process contributed high environmental impact potentials that were mainly generated from water consumption in recirculating water wall paint booth to capture the paint overspray and exhaust solvent vapor. Therefore, the appropriate water consumption strategy should be conducted at solvent-based paint coating process to reduce the amount of water consumption. The improvement method was proposed by using a paper filter booth instead of a recirculating water wall paint booth for small batch painting. This proposed improvement could reduce the water consumption in solvent-based paint coating process to approximate 50-60% (based on the Cleaner Production Case Study of ILEC Appliances Company, Australia).

The new coating process has been proposed to use in the solvent-based paint coating process of Sanyo Universal Electric Public Company Limited (SUE) and it is assumed that 50% of amount of water use can be reduced. However, the environmental impact potentials from the paper filter production installed in the new coating process were excluded. As a result, the comparison of environmental impact potentials between 2 coating processes can be summarized as shown in Table 26.

Table 26 The comparison of environmental impact potentials between the present and the proposed solvent-based paint coating processes

Impact category	Present coating process	Proposed coating process	Unit
Greenhouse effect	160	85.6	kg CO_2
Ozone layer depletion	1.64×10^{-5}	8.26×10^{-6}	kg CFC11
Acidification	0.795	0.432	kg SO_2
Eutrophication	0.0874	0.063	kg PO_4
Summer smog	1.46	0.731	kg C_2H_4
Heavy metals	0.000285	0.000214	kg Pb
Carcinogens	7.03×10^{-5}	3.51×10^{-5}	kg B(a)P
Energy resources	8160	4240	MJ LHV
Solid waste	82.6	41.4	kg

From Table 26, it could be clearly seen that the environmental impact potentials of the proposed solvent-based paint coating process can be greatly reduced in all impact categories (25-50% of the environmental impact potentials of the present solvent-based paint process can be reduced).

The total environmental impact scores of the entire life cycle of solvent-based paint which used the proposed solvent-based paint coating process have been evaluated and compared with solvent-based paint which used the present solvent-based paint coating process (Figure 40).

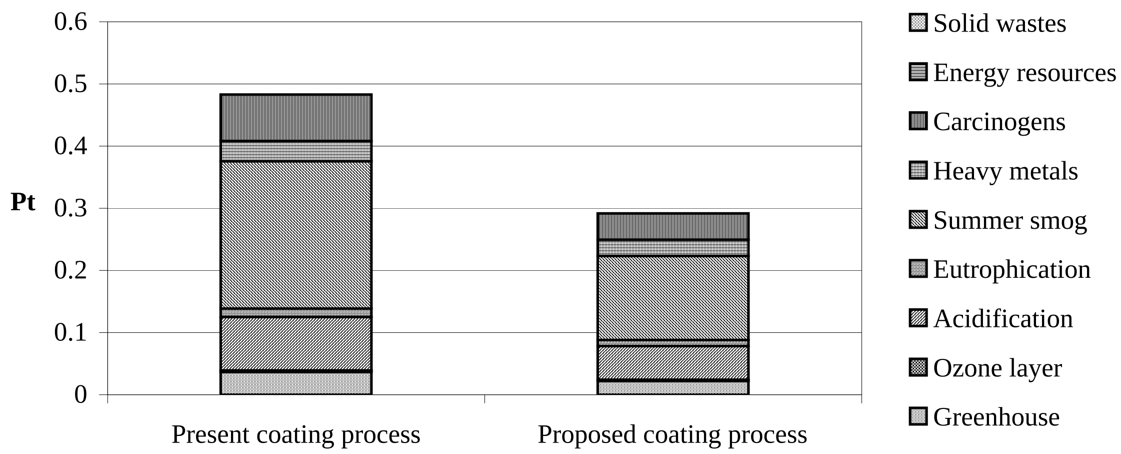


Figure 40 Comparing environmental impacts of the entire life cycle of solvent-based paint life cycle that used the proposed solvent-based paint coating process instead of the present solvent-based paint coating process

From Figure 40, it was found that the total environmental impact potentials of the entire life cycle of solvent-based paint coating process calculated from the proposed solvent-based paint coating process could reduced up to 39% of environmental impacts.

The reduction of impact potentials in the solvent-based paint coating process resulting from the proposed improvement is significantly high of which makes this improvement become interestingly and practically.

CONCLUSIONS

This research used life cycle assessment technique to evaluate the environmental impact associated with the manufacturing of 3 types of paint used in the refrigerator industries which were polyester TGIC powder coatings, polyester-epoxy powder coating, and solvent-based paints. SimaPro 5.1 software with Eco-indicator 95 method was used to estimate the quantitative environmental load from their paints. The life cycle inventory data of 3 types of paint used in the refrigerator industries was collected. The research was based on data from Jotun Powder Coatings (Thailand) company, Nippon Paint (Thailand) company, Sanyo Universal Electric Public Company Limited (SUE) and General Environmental Conservation Public Company Limited (GENCO) in the parts of powder coatings production, solvent-based paint production, coating paint on workpiece process, and disposal process, respectively. Moreover, some of raw materials production data from SimaPro 5.1 database and literatures were used.

From utility databases of Thailand and SimaPro, it was found that the solvent-based paint has relatively higher environmental impact than those of polyester TGIC and polyester-epoxy powder coating paints, respectively. Using the utility database of Thailand, impact categories consisted of summer smog, acidification, and carcinogens showed the largest environmental impact score. The iron used as raw materials for the construction of tap water production plant was the main cause to produce the environmental impact of those impact categories because of the large amount of water consumption. In case of using the utility database of SimaPro, however, acidification and heavy metals were significant impact categories.

The coating phase generated the highest environmental impact in life cycle of paints. The different hot spot of coating phase was presented in life cycle of polyester TGIC powder coating and polyester-epoxy powder coating paints due to the effect from using two different sources of utility database. The pretreatment process and the coating process mainly contributed to the environmental impact in the coating phase when the utility databases of Thailand and SimaPro were used, respectively. This was because the environmental impact potentials of water production in Thailand were relatively higher than that of the European countries. Water consumption was the main cause as it generated the highest environmental impact in the pretreatment process, while the electricity consumption was the main cause of the coating process.

In case of solvent-based paint, the coating process revealed the highest environmental impact contribution in the coating phase obtained from both utility data sources. However, as the result from using two different sources of utility database, the different hot spots of coating process were indicated. This was because the environmental impact of water production in Thailand was more than that of the European country. Therefore, the water consumption was the main cause for generated the highest environmental impact of the coating process which was calculated using the utility databases of Thailand. On the other hand, the electricity consumption and emission in the coating process were main causes to produce the highest environmental impact when the utility database of SimaPro was used to calculate the environmental impact.

The option for reducing the environmental impact of paints used the utility database of Thailand was proposed by the reduction of water consumption in the coating phase. The installation of water-saving devices such as shut-off valve, pressure gauge, control valve and automated conductivity meter to prevent overflow was considered as very promising improvement for powder coating paint due to the reduction of 50% of water consumption in the pretreatment process. Furthermore, it was suggested that the environmental impact of solvent-based paints could be decreased by the replacement the existing recirculating water wall paint booth with a paper filter booth for small batch runs. As the result, the environmental life cycle impact of paints including polyester TGIC powder coatings, polyester-epoxy powder coating, and solvent-based paints could be reduced up to 36-39%.

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APPENDIX

APPENDIX A

CHARACTERIZATION, NORMALIZATION AND WEIGHTING FACTOR OF ECO-INDICATOR 95

Appendix Table A1 Characterization factor of Eco-indicator 95

Greenhouse (kg CO_2 Equivalent)

Compartment	Substance	Factor	Unit
Airborne emission	1,1,1-trichloroethane	100	kg
Airborne emission	CFC-11	3400	kg
Airborne emission	CFC-113	4500	kg
Airborne emission	CFC-114	7000	kg
Airborne emission	CFC-115	7000	kg
Airborne emission	CFC-116	6200	kg
Airborne emission	CFC-12	7100	kg
Airborne emission	CFC-13	13000	kg
Airborne emission	CFC-14	4500	kg
Airborne emission	CFC (hard)	7100	kg
Airborne emission	CFC (soft)	1600	kg
Airborne emission	CO_2	1	kg
Airborne emission	CO_2 (soft)	1	kg
Airborne emission	dichloromethane	15	kg
Airborne emission	HOLON-1211	4900	kg
Airborne emission	HOLON-1301	4900	kg
Airborne emission	HCFC-123	90	kg
Airborne emission	HCFC-124	440	kg
Airborne emission	HCFC-141b	580	kg
Airborne emission	HCFC-142b	1800	kg
Airborne emission	HCFC-22	1600	kg
Airborne emission	HFC-125	3400	kg
Airborne emission	HFC-134a	1200	kg
Airborne emission	HFC-143a	3800	kg
Airborne emission	HFC-152a	150	kg
Airborne emission	methane	11	kg
Airborne emission	N_2O	270	kg
Airborne emission	tetrachloromethane	1300	kg
Airborne emission	trichloromethane	25	kg

Ozone layer (kg CFC11)

Compartment	Substance	Factor	Unit
Airborne emission	1,1,1-trichloroethane	0.12	kg
Airborne emission	CFC-11	1	kg
Airborne emission	CFC-113	1.07	kg
Airborne emission	CFC-114	0.8	kg
Airborne emission	CFC-115	0.5	kg
Airborne emission	CFC-12	1	kg

Ozone layer (kg CFC11) (Cont'd)

Compartment	Substance	Factor	Unit
Airborne emission	CFC-13	1	kg
Airborne emission	CFC (hard)	1	kg
Airborne emission	CFC (soft)	0.055	kg
Airborne emission	HOLON-1201	1.4	kg
Airborne emission	HOLON-1202	1.25	kg
Airborne emission	HOLON-1211	4	kg
Airborne emission	HOLON-1301	16	kg
Airborne emission	HOLON-2311	0.14	kg
Airborne emission	HOLON-2401	0.25	kg
Airborne emission	HOLON-2402	7	kg
Airborne emission	HCFC-123	0.02	kg
Airborne emission	HCFC-124	0.022	kg
Airborne emission	HCFC-141b	0.11	kg
Airborne emission	HCFC-142b	0.065	kg
Airborne emission	HCFC-22	0.055	kg
Airborne emission	HCFC-225ca	0.025	kg
Airborne emission	HCFC-225cb	0.033	kg
Airborne emission	Methyl bromide	0.6	kg
Airborne emission	tetrachloromethane	1.08	kg

Acidification (kg SO_2)

Compartment	Substance	Factor	Unit
Airborne emission	ammonia	1.88	kg
Airborne emission	HCl	0.88	kg
Airborne emission	HF	1.6	kg
Airborne emission	NOx	0.7	kg
Airborne emission	NOx (as NO_2)	0.7	kg
Airborne emission	SO_2	1	kg
Airborne emission	SOx	1	kg
Airborne emission	NO	1.07	kg
Airborne emission	NO_2	0.7	kg
Airborne emission	SOx	1	kg

Eutrophication (kg PO_4)

Compartment	Substance	Factor	Unit
Airborne emission	ammonia	0.33	kg
Airborne emission	NOx	0.13	kg
Airborne emission	NOx (as NO_2)	0.13	kg
Waterborne emission	Kjeldahl-N	0.42	kg
Waterborne emission	COD	0.022	kg

Eutrophication (kg PO_4) (Cont'd)

Compartment	Substance	Factor	Unit
Waterborne emission	N-tot	0.42	kg
Waterborne emission	NH^{4+}	0.33	kg
Waterborne emission	nitrate	0.1	kg
Waterborne emission	P-tot	3.06	kg
Waterborne emission	phosphate	1	kg
Airborne emission	nitrates	0.1	kg
Airborne emission	NO	0.2	kg
Airborne emission	NO_2	0.13	kg
Airborne emission	P	3.06	kg
Airborne emission	phosphate	1	kg
Waterborne emission	NH_3	0.33	kg

Heavy matels (kg Pb)

Compartment	Substance	Factor	Unit
Waterborne emission	Sb	2	kg
Waterborne emission	Mn	0.02	kg
Airborne emission	Heavy matels	1	kg
Airborne emission	Cadmium oxide	50	kg
Waterborne emission	Mo	0.14	kg
Waterborne emission	B	0.03	kg
Waterborne emission	Pb	1	kg
Waterborne emission	Ni	0.5	kg
Waterborne emission	Metallic ions	0.002223	kg
Waterborne emission	Hg	10	kg
Waterborne emission	Cu	0.005	kg
Waterborne emission	Cr	0.2	kg
Waterborne emission	Cd	2	kg
Waterborne emission	Ba	0.02	kg
Waterborne emission	As	1	kg
Airborne emission	Pb	50	kg
Airborne emission	Mn	0.14	kg
Airborne emission	Metals	0.03	kg
Airborne emission	Hg	1	kg
Airborne emission	Cd	0.5	kg

Carcinogen (kg B(a))

Compartment	Substance	Factor	Unit
Airborne emission	benzene	0.000044	kg
Airborne emission	CxHy aromatic	0.000044	kg
Airborne emission	metals	0.0001786	kg

Carcinogen (kg B(a)) (Cont'd)

Compartment	Substance	Factor	Unit
Airborne emission	Ni	0.0044	kg
Airborne emission	PAH's	0.4792	kg
Airborne emission	Acrylonitrile	0.00022	kg
Airborne emission	As	0.044	kg
Airborne emission	Benzo(a)pyrene	1	kg
Airborne emission	Cr(VI)	0.44	kg
Airborne emission	Ethylbenzene	0.000044	kg
Airborne emission	floranthene	1	kg
Airborne emission	tar	0.000044	kg
Airborne emission	vinyl chloride	0.000011	kg

Summer smog (kg C_2H_4)

Compartment	Substance	Factor	Unit
Airborne emission	aldehydes	0.443	kg
Airborne emission	benzene	0.189	kg
Airborne emission	CxHy	0.398	kg
Airborne emission	CxHy aromatic	0.761	kg
Airborne emission	CxHy chloro	0.021	kg
Airborne emission	CxHy halogenated	0.021	kg
Airborne emission	methane	0.007	kg
Airborne emission	Non methane VOC	0.416	kg
Airborne emission	PAH's	0.04932	kg
Airborne emission	pentane	0.408	kg
Airborne emission	VOC	0.398	kg
Airborne emission	1,1,1-trichloroethane	0.021	kg
Airborne emission	1,2-dichloroethane	0.021	kg
Airborne emission	acetadehyde	0.527	kg
Airborne emission	acetone	0.178	kg
Airborne emission	acetonitrile	0.416	kg
Airborne emission	acrolein	0.603	kg
Airborne emission	acrylonitrile	0.416	kg
Airborne emission	alcohols	0.196	kg
Airborne emission	alkanes	0.398	kg
Airborne emission	alkenes	0.906	kg
Airborne emission	benzaldehyde	0.334	kg
Airborne emission	benzo(a)pyrene	0.761	kg
Airborne emission	butane	0.41	kg
Airborne emission	butene	0.992	kg
Airborne emission	caprolactam	0.761	kg
Airborne emission	chlorophenols	0.021	kg
Airborne emission	crude oil	0.398	kg

Summer smog (kg C_2H_4) (Cont'd)

Compartment	Substance	Factor	Unit
Airborne emission	CxHy aliphatic	0.398	kg
Airborne emission	cycloalkanes	0.398	kg
Airborne emission	dichloromethane	0.021	kg
Airborne emission	diethyl ether	0.39	kg
Airborne emission	diphenyl	0.761	kg
Airborne emission	ethane	0.082	kg
Airborne emission	ethanol	0.268	kg
Airborne emission	ethene	1	kg
Airborne emission	ethylbenzene	0.593	kg
Airborne emission	ethylene glycol	0.196	kg
Airborne emission	ethylene oxide	0.377	kg
Airborne emission	ethyne	0.168	kg
Airborne emission	formaldehyde	0.421	kg
Airborne emission	haptane	0.529	kg
Airborne emission	hexachlorobiphenyl	0.761	kg
Airborne emission	haxane	0.421	kg
Airborne emission	Hydroxyl compounds	0.377	kg
Airborne emission	isopropanol	0.196	kg
Airborne emission	kerosene	0.398	kg
Airborne emission	ketones	0.326	kg
Airborne emission	methanol	0.123	kg
Airborne emission	methyl ethyl ketone	0.473	kg
Airborne emission	methyl mercaptane	0.377	kg
Airborne emission	naphthalene	0.761	kg
Airborne emission	pentachlorophenol	0.021	kg
Airborne emission	petrol	0.398	kg
Airborne emission	phenol	0.761	kg
Airborne emission	phthalic and anhydride	0.761	kg
Airborne emission	propane	0.42	kg
Airborne emission	propene	1.03	kg
Airborne emission	propionic acid	0.377	kg
Airborne emission	styrene	0.761	kg
Airborne emission	tar	0.416	kg
Airborne emission	terpentine	0.377	kg
Airborne emission	tetrachloroethene	0.05	kg
Airborne emission	tetrachloromethane	0.021	kg
Airborne emission	toluene	0.563	kg
Airborne emission	trichloroethene	0.021	kg
Airborne emission	trichloromethane	0.021	kg
Airborne emission	vinyl acetate	0.223	kg
Airborne emission	vinyl chloride	0.021	kg
Airborne emission	VOC	0.398	kg

Energy resources (MJ LHV)

Compartment	Substance	Factor	Unit
Raw material	barrage water	0.01	kg
Raw material	biomass (feedstock)	1	MJ
Raw material	coal	29.3	kg
Raw material	coal (feedstock) FAL	26.4	kg
Raw material	coal ETH	18	kg
Raw material	coal FAL	26.4	kg
Raw material	crude oil	41	kg
Raw material	crude oil (feedstock)	41	kg
Raw material	crude oil (feedstock) FAL	42	kg
Raw material	crude oil ETH	42	kg
Raw material	crude oil FAL	42	kg
Raw material	crude oil IDEMAT	42.7	kg
Raw material	energy (undef.)	1	MJ
Raw material	energy from coal	1	MJ
Raw material	energy from hydro power	1	MJ
Raw material	energy from lignite	1	MJ
Raw material	energy from natural gas	1	MJ
Raw material	energy from oil	1	MJ
Raw material	energy from uranium	1	MJ
Raw material	energy from wood	1	MJ
Raw material	energy recovered	1	MJ
Raw material	gas from oil production	40.9	m^3
Raw material	lignite	10	kg
Raw material	lignite ETH	8	kg
Raw material	methane (kg)	35.9	kg
Raw material	natural gas	30.3	kg
Raw material	natural gas (feedstock)	35	m3
Raw material	natural gas (feedstock) FAL	46.8	kg
Raw material	natural gas (vol)	36.6	m3
Raw material	natural gas ETH	35	m3
Raw material	natural gas FAL	46.8	kg
Raw material	petroleum gas ETH	35	m^3
Raw material	pot.energy hydropower	1	MJ
Raw material	steam from waste incineration	1	MJ
Raw material	unspecified energy	1	MJ
Raw material	uranium (in ore)	451000	kg
Raw material	uranium (ore)	1110	kg
Raw material	uranium FAL	2291	g
Raw material	wood	15.3	kg
Raw material	wood (feedstock)	15.3	kg
Raw material	wood and wood wastes FAL	9.5	kg

Solid waste (kg)

Compartment	Substance	Factor	Unit
Solid emission	aluminium	1	kg
Solid emission	aluminium scrap	1	kg
Solid emission	asbestos	1	kg
Solid emission	bilge oil waste	1	kg
Solid emission	bulk waste	1	kg
Solid emission	calciumfluoride	1	kg
Solid emission	cardboard	1	kg
Solid emission	cathode iron ingots	1	kg
Solid emission	cathode loss	1	kg
Solid emission	chemical waste	1	kg
Solid emission	chemical waste (inert)	1	kg
Solid emission	chemical waste (regulated)	1	kg
Solid emission	chromium compounds	1	kg
Solid emission	coal ash	1	kg
Solid emission	construction waste	1	kg
Solid emission	copper foil	1	kg
Solid emission	copper scrap	1	kg
Solid emission	corr. Cardboard rejects	1	kg
Solid emission	dross	1	kg
Solid emission	dross for recycling	1	kg
Solid emission	dust-not specified	1	kg
Solid emission	dust, break-out	1	kg
Solid emission	electrostatic filter dust	1	kg
Solid emission	final waste (inert)	1	kg
Solid emission	fly ash	1	kg
Solid emission	glass	1	kg
Solid emission	Incinerator waste	1	kg
Solid emission	industrial waste	1	kg
Solid emission	inorganic general	1	kg
Solid emission	Iron compounds	1	kg
Solid emission	metal scrap	1	kg
Solid emission	mineral waste	1	kg
Solid emission	mineral waste (mining)	1	kg
Solid emission	mixed plastics	1	kg
Solid emission	oil	1	kg
Solid emission	oil separator sludge	1	kg
Solid emission	other waste	1	kg
Solid emission	packaging waste	1	kg
Solid emission	paper/borad packaging	1	kg
Solid emission	PE	1	kg
Solid emission	plastic production waste	1	kg
Solid emission	plastic packaging	1	kg

Solid waste (kg) (Cont'd)

Compartment	Substance	Factor	Unit
Solid emission	printed circuitboard	1	kg
Solid emission	process waste	1	kg
Solid emission	prod. waste unspecified	1	kg
Solid emission	produc. waste (not inert)	1	kg
Solid emission	PVC	1	kg
Solid emission	radioactive waste	1	kg
Solid emission	rejects	1	kg
Solid emission	residues	1	kg
Solid emission	slag	1	kg
Solid emission	slags/ash	1	kg
Solid emission	sludge	1	kg
Solid emission	solid waste	1	kg
Solid emission	soot	1	kg
Solid emission	steel packaging	1	kg
Solid emission	steel scrap	1	kg
Solid emission	stones and rubble	1	kg
Solid emission	tin	1	kg
Solid emission	tin compounds	1	kg
Solid emission	tinder from rollong drum	1	kg
Solid emission	toxic waste	1	kg
Solid emission	unspecified	1	kg
Solid emission	waste	1	kg
Solid emission	waste bioactive	1	kg
Solid emission	waste bioactive landfill	1	kg
Solid emission	waste in incineration	1	kg
Solid emission	waste in inert landfill	1	kg
Solid emission	waste limesone	1	kg
Solid emission	waste to recycling	1	kg
Solid emission	wood	1	kg
Solid emission	wood (sawdust)	1	kg
Solid emission	wood packaging	1	kg
Solid emission	zinc	1	kg

Source: PRé Consultants (2000)

Appendix Table A2   Normalization and weighting factor of Eco-indicator 95

Impact Category	Normalization	Weighting
Greenhouse	0.0000765	2.5
Ozone layer	1.08	100
Acidification	0.00888	10
Eutrophication	0.0262	5
Heavy metal	18.4	5
Carcinogens	92	10
Winter smog	0.0106	5
Summer smog	0.0558	2.5
Pesticides	1.04	25
Energy resources	0.00000629	0
Solid waste	0	0

Source: PRé Consultants (2000)

APPENDIX B

INPUT AND OUTPUT IN THE RAW MATERIALS PRODUCTION

Appendix Table B1 Input and output in the soda ash production

		Products		
Products and co-products	Amount	Unit	% Allocation	Waste type
Na_2CO_3	1	Ton	100 %	
		Inputs		
Resources	Amount	Unit	Comment	
Cooling water	50 -100	m^3		
Water in process	2.5 - 3.6	m^3		
Materials/fuels	Amount	Unit	Comment	
Limestone	2140-3420	kg		
Raw brine	6030-7000	kg		
NH_3 make up	0.8-2.1	kg		
Fuels	9.7-13.8	GJ		
Electricity	50-130	kWh		
		Outputs		
Emissions to air	Amount	Unit	Comment	
CO_2	200-400	kg		
CO	4-20	kg		
NH_3	< 1.5	kg		
Dust	< 0.2	kg		
Emissions to water	Amount	Unit	Comment	
Cl^-	850-1100	kg		
Ca^{2+}	340-400	kg		
Na^+	160-220	kg		
SO_4^{2+}	1-11	kg		
NH_4^+	0.3-2	kg		
Suspended solids	90-700	kg		
Solid emissions	Amount	Unit	Comment	
Fines of limestone	30-300	kg		
Non recycled grits at slaker	10-120	kg		

Source: European Soda Ash Producers Association (2004)

Appendix Table B2 Input and output in the triglycidyl isocyanurate (TGIC) production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Triglycidyl isocyanurate	1	kg	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Epichlorohydrin I	6.34	kg	
Water-Thai	7.101	kg	
NaOH (100%)	0.584	kg	
Methanol	4.876	kg	
Methanol Plant	4E-10	p	
Electricity-Thai	0.7029	kWh	

Outputs			
Emissions to air	Amount	Unit	Comment
Methanol	4.876	kg	
Epichlorohydrin	5.07	kg	

Emissions to water	Amount	Unit	Comment
NaCl	0.847	kg	
Na	0.003163	kg	
OH-	0.002338	kg	
Water	7.375	kg	

Solid emissions	Amount	Unit	Comment
Chemical waste	0.219	kg	

Source: SciFinder Scholor (2005)

Appendix Table B3 Input and output in the carboxyl polyester resin production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Carboxyl polyester resin	1	kg	100 %	

Inputs			
Resources	Amount	Unit	Comment
Cooling water	0.024	m^3	
Water	0.006	m^3	

Materials/fuels	Amount	Unit	Comment
Terephthalic acid	0.653	kg	
Apidic acid	0.0725	kg	
Ethylene oxide/glycol ETH U	0.417	kg	
Isopropanol	0.0096	kg	
Methanol plant	4E-10	p	
Electricity MV use in UCPTE U	0.013	kWh	
Heat industrial coal furnace 1-10MW U	0.95	MJ	
Heat industrial furnace >100kW U	1.42	MJ	
Heat industrial furnace S CH U	0.56	MJ	
Fuel oil low S in boiler 1MW U	0.125	MJ	
Truck 40t ETH U	0.133	tkm	
Rail transport ETH U	0.801	tkm	

Outputs			
Emissions to air	Amount	Unit	Comment
Heat waste	0.0468	MJ	

Emissions to water	Amount	Unit	Comment
COD	0.002	kg	
Water	0.153	kg	

Source: Shell Chemical (2000)

Appendix Table B4 Input and output in the epoxy resin production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Epoxy resin I	1	kg	100 %	Plastics
HCl	0.124	kg	0 %	Others

Inputs			
Materials/fuels	Amount	Unit	Comment
Bisphenol A I	313	g	
Epichlorohydrin I	687	g	
Crude oil N-sea(b) I	3.9	kg	

Outputs			
Non material emission	Amount	Unit	Comment
Occup. as industrial area	0.00557	m^2a	

Source: SimaPro 5.1 Program (2005)

Appendix Table B5 Input and output in the filler (powder coating) production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Filler (powder coating)	1	kg	100 %	Others

Inputs			
Materials/fuels	Amount	Unit	Comment
Lime stone B250	0.5455	kg	
Barite, at plant/RER U	0.4545	kg	

Source: Jotun Powder Coatings (Thailand) Limited (2004)

Appendix Table B6 Input and output in the pigment (powder coating) production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Pigment (powder coating)	1	kg	100 %	Others

Inputs			
Materials/fuels	Amount	Unit	Comment
TiO_2	0.9983	kg	
Pigments (general) I	0.0017	kg	

Source: Jotun Powder Coatings (Thailand) Limited (2004)

Appendix Table B7 Input and output in the resin (solvent-base paint) production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Resin (solvent-base paint)	1	kg	100 %	Others

Inputs			
Materials/fuels	Amount	Unit	Comment
Acrylic binder 34%	0.7316	kg	
Epoxy resin I	0.0765	kg	
Melamineformaldehyde I	0.1919	kg	

Source: Nippon Paint Company (Thailand) Limited (2004)

Appendix Table B8 Input and output in the pigment (solvent-base paint) production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Pigment (solvent-base paint)	1	kg	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
TiO_2	0.9989	kg	
Pigments (general) I	0.0011	kg	

Source: Nippon Paint Company (Thailand) Limited (2004)

Appendix Table B9 Input and output in the solvent production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Solvent	1	kg	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
1-Butanol	0.1575	kg	
Xylenes A	0.0416	kg	
Aromatics	0.4400	kg	
Diethylene glycol	0.3490	kg	
Methyl ethyl ketone	0.0120	kg	

Source: Nippon Paint Company (Thailand) (2004) Limited

Appendix Table B10   Input and output in the thinner production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Thinner	1	kg	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Aromatics	0.42	kg	
Toluene A	0.23	kg	
Xylenes A	0.28	kg	
Diethylene glycol	0.07	kg	

Source: Nippon Paint Company (Thailand) (2004) Limited

Appendix Table B11   Input and output in the benzoin production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Benzoin	1	kg	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Benzadehyde	1.087	kg	
Isopropanol	2.500	kg	
HCN A	0.216	kg	

Source: MiraCosta College (2005)

Appendix Table B12 Input and output in the benzadehyde production

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Benzadehyde	1	kg	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Toluene A	2.16975	kg	
Oxygen B250	0.75470	kg	
Cobalt I	0.02500	kg	
Electricity-Thai	1.01	kWh	

Source: Faiz Ahmed Faisal Kaskar (2005)

APPENDIX C

THE DETAIL OF ELECTRICITY AND WATER GENERATION

Appendix Table C1 Electricity of Thailand base 2000

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Electricity Thailand base 2000	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Coal Power Plant	0.2284	kWh	
Combine Power Plant	0.3741	kWh	
Diesel Power Plant	0.000039	kWh	
Gas Power Plant	0.0169	kWh	
Hydro power Plant	0.0778	kWh	
Thermal Power Plant	0.3027	kWh	

Source: Viganda, V. (2002)

Appendix Table C2 Hydro power plant

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Hydro power plant	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Cement (Portland) I	1.99E-06	kg	
Concrete I	0.0207	kg	
Steel I	0.00055	kg	
X22CrNi17 (431) I	0.000368	kg	

Source: Viganda, V. (2002)

Appendix Table C3 Coal power plant

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Coal Power Plant	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Concrete I	0.000572	kg	
Steel I	0.00055	kg	
X22CrNi17 (431) I	0.000195	kg	
Copper I	2.14E-07	kg	
Aluminium rec. I	9.63E-09	kg	

Electricity/heat	Amount	Unit	Comment
Natural gas I	0.00814	kg	
Crude oil I	5.25E-05	kg	
Diesel I	0.00414	kg	
Crude lignite	0.961	kg	

Outputs			
Emissions to air	Amount	Unit	Comment
CO_2	1.3889	kg	
CO	2.16E-05	kg	
N_2O	4.32E-05	kg	
NOx	0.00637	kg	
VOC	2.16E-05	kg	
Methane	1.62E-05	kg	
Dust	5.52E-05	kg	
SO_2	0.00348	kg	

Source: Viganda, V. (2002)

Appendix Table C4 Combine power plant

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Combine power plant	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Concrete I	0.00052	kg	
Steel I	0.000415	kg	
X22CrNi17 (431) I	0.000177	kg	
Copper I	6.54E-09	kg	
Aluminium rec. I	3.7E-09	kg	

Electricity/heat	Amount	Unit	Comment
Natural gas I	0.281	kg	
Crude oil I	1.23E-05	kg	
Diesel I	0.000436	kg	
Crude lignite	0	kg	

Outputs			
Emissions to air	Amount	Unit	Comment
CO_2	0.00101	kg	
CO	2.16E-07	kg	
N_2O	2.8E-08	kg	
NOx	2.72E-06	kg	
VOC	6.46E-08	kg	
Methane	9.6E-09	kg	
Dust	2.44E-07	kg	
SO_2	4.21E-09	kg	

Source: Viganda, V. (2002)

Appendix Table C5 Diesel power plant

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Diesel power plant	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Concrete I	0.00595	kg	
Steel I	0.00429	kg	
X22CrNi17 (431) I	0.00202	kg	
Copper I	1.32E-08	kg	
Aluminium rec. I	7.42E-09	kg	

Electricity/heat	Amount	Unit	Comment
Natural gas I	0.00293	kg	
Crude oil I	0.00757	kg	
Diesel I	0.295	kg	
Crude lignite	0	kg	

Outputs			
Emissions to air	Amount	Unit	Comment
CO_2	0.769	kg	
CO	0.000406	kg	
N_2O	0.000122	kg	
NOx	0.00284	kg	
VOC	4.06E-05	kg	
Methane	0	kg	
Dust	0.000146	kg	
SO_2	0.000406	kg	

Source: Viganda, V. (2002)

Appendix Table C6 Gas power plant

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Gas power plant	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Concrete I	0.000506	kg	
Steel I	0.00149	kg	
X22CrNi17 (431) I	0.00108	kg	
Copper I	1.08E-08	kg	
Aluminium rec. I	6.18E-09	kg	

Electricity/heat	Amount	Unit	Comment
Natural gas I	0.465	kg	
Crude oil I	2.92E-05	kg	
Diesel I	7.78E-06	kg	
Crude lignite	0	kg	

Outputs			
Emissions to air	Amount	Unit	Comment
CO_2	0.00099	kg	
CO	5.71E-07	kg	
N_2O	9.28E-09	kg	
NOx	3.35E-05	kg	
VOC	7.14E-08	kg	
Methane	1.05E-07	kg	
Dust	1.76E-08	kg	
SO_2	1.99E-15	kg	

Source: Viganda, V. (2002)

Appendix Table C7 Thermal power plant

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Thermal power plant	1	kWh	100 %	

Inputs			
Materials/fuels	Amount	Unit	Comment
Concrete I	0.000678	kg	
Steel I	0.000529	kg	
X22CrNi17 (431) I	0.000231	kg	
Copper I	1.02E-08	kg	
Aluminium rec. I	5.73E-09	kg	

Electricity/heat	Amount	Unit	Comment
Natural gas I	0.157	kg	
Crude oil I	0.15	kg	
Diesel I	0.000931	kg	
Crude lignite	0	kg	

Outputs			
Emissions to air	Amount	Unit	Comment
CO_2	0.00105	kg	
CO	2.7E-07	kg	
N_2O	2.91E-08	kg	
NOx	2.9E-06	kg	
VOC	6.59E-08	kg	
Methane	1.53E-08	kg	
Dust	2.52E-07	kg	
SO_2	4.59E-09	kg	

Source: Viganda, V. (2002)

Appendix Table C8 Water of Thailand

Products				
Products and co-products	Amount	Unit	% Allocation	Waste type
Water-Thai	1	kg	100 %	

Inputs			
Resources	Amount	Unit	Comment
Water	1040.29	g	

Materials/fuels	Amount	Unit	Comment
Iron	266.852	g	
Concrete I	2.1029	g	
Concrete (reinforced) I	3.318	g	
Cement (Portland) I	13.895	g	
NaOH ETH S	34.538	g	
Lime I	0.585	g	

Electricity/heat	Amount	Unit	Comment
Electricity-Thai	0.1302	kWh	

Outputs			
Emissions to water	Amount	Unit	Comment
Waste water (vol)	12.786	cm^3	

Source: Nongnuch, P. (2004)

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