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Sustainable manufacturing: a case study of the forklift painting process

Junbeum Kim[a]*, Kwangho Park[b], Yongwoo Hwang[b] and Ildo Park[c]

[a]*Center for Earth Systems Engineering and Management, Department of Civil, Environmental and Sustainable Engineering, Arizona State University, PO Box 875306, Tempe, AZ 85287-5306, USA;* [b]*Department of Environmental Engineering, Inha University, 253, Namgu, Inchon, South Korea;* [c]*Production Technology Team, Daewoo Heavy Industries Ltd., Incheon, South Korea*

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Life cycle assessment (LCA) and design for environment (DFE) methods were applied to assess opportunities for reducing the environmental impacts of forklift manufacturing unit processes and to redesign those unit processes to increase overall sustainability. The unit processes of forklift manufacture generating the most environmental emissions were identified by applying LCA methodology. The results show that eco-toxicity and human toxicity were the most significant impacts of the forklift manufacturing process overall. Also, within the manufacturing unit processes, cutting, welding and painting had the highest impact values. In order to minimise environmental impacts, a new paint was created with increased solid content over the existing solvent paint used in the painting process. In addition, by applying DFE methodology and the high solid paint, overcoat and drying steps were eliminated from the forklift painting process. As a result, the environmental index of a follow-up LCA showed that environmental impacts could be reduced by 20%, while volatile organic compound (VOC) and paint usage could be decreased by 30% and 20%, respectively.

Keywords: sustainable manufacturing process; life cycle assessment (LCA); design for environment (DFE); environmental impacts; forklift; high solid paint

1. Introduction

Traditionally both governments and industries have tended to focus their environmental policies and programmes towards addressing process-related environmental impacts resulting from manufacturing activities. Large investments by companies towards 'end-of-pipe' technologies to manage air and water emissions were a common practice in the 1980s. However, recently there has been a shift in focus from process-type considerations to more of a product-focused approach. By viewing environmental impacts from a product perspective, the entire life cycle of the product is considered: from raw material extraction to end-of-life disposition. Many governments and international organisations have recently been developing product-focused policies and regulations, voluntary product stewardship initiatives, mandatory extended producer responsibility (EPR) programmes, integrated product policy (IPP) as well as expanded environmental criteria for procurement and environmental labelling schemes (Commission of the European Communities 2003, Kim *et al.* 2004, Heijungs *et al.* 2006).

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*Corresponding author. Email: Junbeum.Kim@asu.edu

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One of the methods for pollution prevention and sustainable production approaches is design for environment (DFE) (Allenby 1992, Graedel and Allenby 2003, Rahimifard and Clegg 2007). DFE is the systematic integration of environmental considerations into materials, product and unit process design. Because it offers new perspectives with a product and business focus, DFE can be a powerful tool to make companies more competitive and more innovative as well as more environmentally responsible. Also, DFE provides an organised structure into which companies can integrate most features of sustainable development such as eco-efficiency, pollution prevention and clean production.

One of the tools to support environmentally friendly product design is life cycle assessment (LCA). LCA is a tool used for assessing the environmental impacts associated with a specific product or service. The application of the process and associated waste minimisation practices by management, design and manufacturing can lead to better and less-polluting products (ISO[1] 14040 1997).

LCA and DFE are methods of gathering information and translating it into useful forms that designers and decision-makers can use to make environmentally-preferable choices. Both methodologies are information-intensive and require the development of several information and knowledge data sets for full integration into design and decision models (Richards and Fullerton 1994, Graedel and Allenby 2003).

These methods can be applied to every industry and product system (Herrmann 2001, IEEE 1993–2007). The Ministry of Environment in South Korea promotes the application of the environmental declaration of products (EDP) system (MOE 2002, KNCPC 2005), which is based on the ISO 14040s LCA and ISO/TRI 14025 (Type III) standards, to all industrial systems and products. Adoption and application of these methods help promote sustainable production approaches in South Korea. The EDP System can contribute to the purchase of environmentally-friendly products by providing environmental information on products to the customers, and promoting environmentally-friendly product manufacturing and clean production technology.

Many environmental approaches are linked to the technologies involved in the production, distribution and use of commercial and industrial products, as well as economic and social aspects. Understanding the process of innovation and considering its economic and social aspects will be needed in any effort to pursue sustainable production and system.

In this study, LCA and DFE for sustainable production were applied to unit processes involved in forklift manufacturing. To put it simply, forklift manufacturing unit processes with the greatest environmental impacts were identified using the LCA method. Then, based on the results of the LCA, the DFE method was applied to reduce environmental impacts in the highest-impact unit processes.

2. LCA in the forklift production process

A product life cycle begins with raw materials production and extends to manufacture, transport, use, and disposal. LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, process, or system. The formal structure of an LCA has four phases as shown in Figure 1. The first phase is to define the goal and scope of the LCA. It involves the identification of materials, processes and products that are to be considered in the evaluation, and how broadly they will be defined. The second

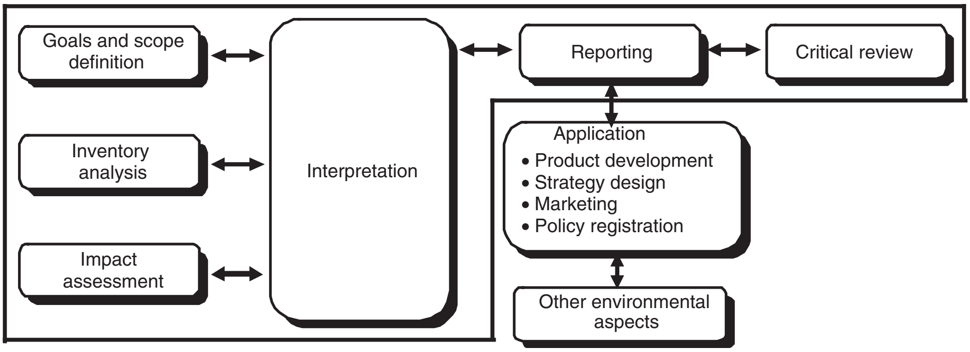

Figure 1. LCA Framework based on ISO 14040 (ISO 14040, 1997).

component of the LCA is the life cycle inventory analysis (LCIA). It uses quantitative data to establish the levels and types of energy and materials used and the releases that result from the industrial processes (e.g. inputs are materials, energy, water, air, etc., and outputs are products, water effluents, airborne emissions, solid waste, etc.). The third phase is the impact analysis; it involves relating the outputs of the system to the impacts on the external world into which those outputs flow. The final phase is interpretation. This is where the findings from one or more of the three stages are used to draw conclusions and make recommendations for reducing environmental impacts (ISO 14040 1997).

2.1 *Goal and scope definition*

The goal of this study is to examine the highest-environmental impact value in the forklift manufacturing unit processes and use basic environmental data to identify alternative designs that will reduce the environmental impacts. The functional unit is a key element of LCA and must be clearly defined. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This study was accomplished by defining the functional unit as one forklift (Model: D25S-3, Manufactured by Daewoo Heavy Industries Ltd) which has 2.5 ton carrying capacity, 3800 mm lift height, 1100 mm fork length, and 2540 mm of length and 1155 mm of width. In South Korea there are four companies producing forklifts. Daewoo Heavy Industries Ltd market share is relatively large and was 60% in 2004. The LCA completed in this study was based on one year of data provided by Daewoo Heavy Industries Ltd.

In this study, the system boundary includes all processes beginning with raw material acquisition and continuing through the manufacturing and shipment processes. Figure 2 shows the system boundary for this study in the life cycle system of a forklift.

2.2 *Life cycle inventory in each manufacturing unit process*

Figure 3 shows the six forklift manufacturing unit processes: cutting and welding, painting, assembly, test run, repair, and shipment. Below are brief descriptions of the various unit processes.

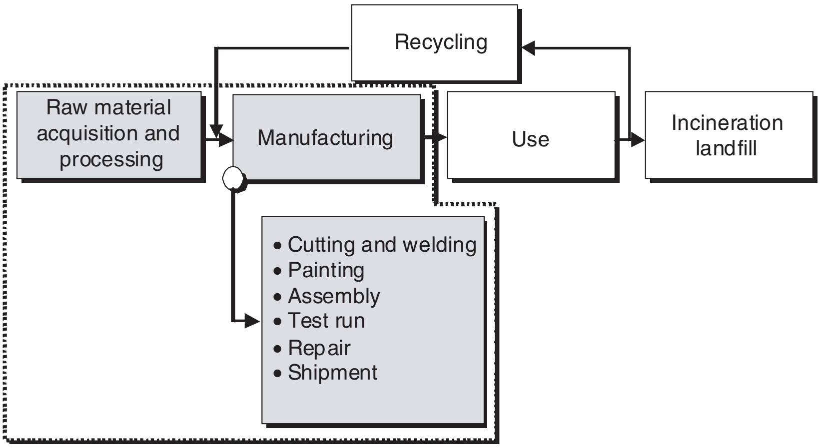

Figure 2. System boundary for this study in the life cycle system of the forklift.

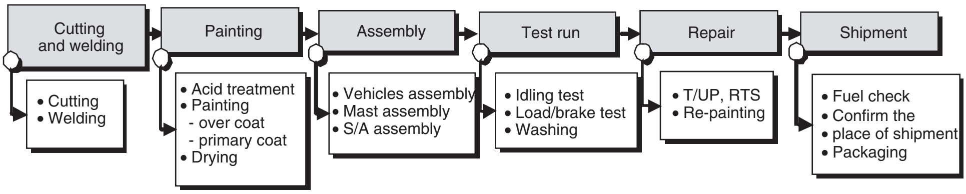

Figure 3. Manufacturing unit processes considered in the forklift production study.

Cutting and welding involves both mechanical and welding processes. The mechanical process consists of cutting and grinding. The welding process may utilise up to three different methods: oxy-fuel welding, laser beam welding (LBW) and gas metal arc welding (GMAW). Oxy-fuel welding is commonly called oxyacetylene welding, oxy welding, or gas welding. In oxy-fuel welding, a welding torch is used to weld metals. Laser beam welding (LBW) is a technique used to join multiple pieces of metal through the use of a laser. The beam provides a concentrated heat source, allowing for narrow, deep welds and high welding rates. GMAW is one of the most versatile and heavily used welding processes today. This is a semi-automatic or automatic arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun (Naidu *et al.* 2003, Cary and Scott 2005). When a forklift is made, the GMAW method is used.

After the cutting and welding unit process is complete, the painting unit process begins for protecting, shape changing (colour, lustre, fine view and mark), and special performance such as optic function, heat function, mechanical function and environmental protection. The painting unit process consists of two steps: acid treatment and large-scale painting (Kim 1999).

The assembly process produces the main body following the sub-assembly of each part. Basically, assembly of a vehicle is a unit process that attaches the engine, tyre assembly, fuel system and mast (lifting attachment) to the forklift main body.

After the assembly process comes the test run. Performance tests such as an idling test, load test and brake test are carried out. Lastly, there is the touch-up painting and

Table 1. Input material and energy in each manufacturing process.

			Manufacturing process					
Item		Unit	Cutting and welding	Painting	Assembly	Test run	Repair	Shipment
Raw materials	Steel	kg	482.2					
	Acrylic polyol resins	kg		9.0		0.05		
	Epoxy resins	kg		6.0			0.9	
	Hydrocarbon	kg			77.28			
	Gasoline	kg			20			
	Ethylene glycol	kg			5.6			
Ancillary materials	CO_2 wire	kg	8.7					
	CO_2 gas	m^3	35.5					
	Cut wire	kg		2.45				
	Sodium silicate	g		40				
	Hydrochloric acid	g		2650				
	Zinc phosphate	g		938				
	Rust preventive oil	g			0.23			0.23
Utility	LPG	kg	0.66	9				
	O_2	m^3	15.16					
	Electricity	kwh	95.8	81.5	36.8	13.4		22.85
	Water	kg		2000		56.5		12.5

Source: Daewoo Heavy Industries Co. Ltd.

re-painting unit process. After going through these unit processes, the forklift fuel system is checked and the unit is packaged for shipping.

Table 1 shows input and output data such as raw materials, ancillary materials and utilities (water, electricity, etc.), which are calculated as per the ISO 14001 certification for the manufacturing process of one forklift (data from Daewoo Heavy Industries Co. Ltd). Based on this data, a life cycle inventory (LCI) of cradle-to-gate material inputs and emissions were compiled using the Korean national LCI database (KAB 2004, KEPI 2004), along with energy and chemical LCI data from TEAM 3.0 and GaBi software (Ecobalance 2008, GaBi 2008). The resulting LCI details for each forklift manufacturing unit process are summarised in Table 2. Primary air emissions are carbon dioxide (CO_2, fossil), carbon monoxide (CO), sulphur oxides (SO_x as SO_2), nitrogen oxides (NO_x as NO_2), methane (CH_4) and hydrocarbons (except methane). The air emissions are discharged mostly in the cutting and welding and painting unit process. Primary water emissions are chlorides (Cl^-), sulphates (SO_4^{2-}), iron (Fe^{2+}, Fe^{3+}), COD (chemical oxygen demand), aluminium (Al^{3+}) and suspended matter (unspecified).

2.3 *Environmental impact of each manufacturing unit process*

Life cycle inventory analysis is aimed at identifying the predominant environmental emissions that result from the processes and products being scrutinised. Therefore, it is difficult to grasp the environmental effects of the product via the LCI alone. For this reason, a life cycle impact assessment (LCIA) phase is undertaken in which the inventory

Table 2. Summarised results of inventory analysis for each process.

			Manufacturing process					
Inventory parameter		Unit	Cutting and welding	Painting	Assembly	Test run	Repair	Shipment
I	(r) Lignite (in ground)	kg	1.35E+05	9.05E+02	8.53E−03	2.68E−05	1.63E−04	9.16E−07
I	(r) Oil (in ground)	kg	1.13E+04	3.97E+02	9.49E+01	3.35E−01	6.59E−01	1.54E−02
I	(r) Natural gas (in ground)	kg	4.87E+04	2.38E+02	4.72E+00	2.43E−02	7.36E−02	2.07E−03
I	(r) Pyrite (FeS_2, ore)	kg	4.67E+00	1.33E+02	1.83E−03	5.95E−06	2.10E−05	9.17E−07
I	(r) Clay (in ground)	kg	8.74E+04	2.99E+00	3.01E−03	2.92E−04	1.74E−04	4.40E−05
I	(r) Uranium (U, ore)	kg	5.75E+00	6.18E−02	3.10E−05	2.52E−05	1.36E−05	3.88E−06
I	(r) Copper (Cu, ore)	kg	8.75E+00	2.14E−03	1.11E−06	3.63E−09	1.28E−08	5.59E−10
I	(r) Manganese (Mn, ore)	kg	1.18E+01	5.71E−07	1.28E−07	4.16E−10	1.47E−09	6.41E−11
O	(a) Carbon dioxide (CO_2, fossil)	g	5.60E+08	6.15E+06	6.23E+04	2.42E+03	1.62E+03	3.48E+02
O	(a) Sulphur oxides (SO_x as SO_2)	g	1.38E+06	4.31E+04	7.07E+02	1.14E+01	9.34E+00	1.45E+00
O	(a) Nitrogen oxides (NO_x as NO_2)	g	1.29E+06	1.85E+04	3.22E+02	3.99E+00	3.85E+00	4.74E−01
O	(a) Methane (CH_4)	g	9.75E+05	1.51E+04	1.18E+02	6.33E+00	7.15E+00	9.72E−01
O	(a) Zinc (Zn)	g	9.39E+01	1.30E+04	2.86E−03	6.86E−04	3.72E−04	1.06E−04
O	(a) Carbon monoxide (CO)	g	2.22E+06	6.50E+03	1.53E+01	1.25E+00	8.14E−01	1.88E−01
O	(a) Organic matter (unspecified)	g	5.65E+05	5.10E+03	6.63E−01	2.33E−03	4.29E−03	4.20E−05
O	(a) Hydrocarbons (except methane)	g	2.13E+05	3.64E+03	2.04E+02	1.09E+00	1.69E+00	1.31E−01
O	(a) Lead (Pb)	g	4.57E+03	2.41E+03	3.86E−03	9.22E−04	5.24E−04	1.42E−04
O	(a) Hydrogen chloride (HCl)	g	6.37E+04	1.84E+03	6.05E−01	4.35E−01	2.34E−01	6.71E−02
O	(a) Silicon (Si)	g	1.43E+00	5.59E+02	1.52E−01	1.36E−01	7.28E−02	2.09E−02

O	(a) Aluminium (Al)	g	1.69E−01	3.08E+02	1.01E−01	9.06E−02	4.86E−02	1.40E−02
O	(a) Alkane (unspecified)	g	1.62E+00	2.91E+02	5.29E−01	1.26E−02	1.20E−02	1.91E−03
O	(a) Nitrous oxide (N_2O)	g	2.85E+03	1.66E+02	7.42E+00	5.41E−02	6.26E−02	4.84E−03
O	(w) Chlorides (Cl^-)	g	2.40E+06	3.62E+04	9.70E+02	9.60E+00	1.02E+01	1.47E+00
O	(w) Sulphates (SO_4^-)	g	1.49E+06	2.54E+04	1.83E+01	1.70E+00	9.32E−01	2.62E−01
O	(w) Sodium (Na^+)	g	1.33E+02	9.75E+03	5.82E+02	3.34E+00	4.84E+00	5.12E−01
O	(w) Calcium (Ca^{++})	g	2.50E+01	3.59E+03	5.99E+01	3.10E−01	4.71E−01	4.76E−02
O	(w) Aluminium ($Al_3{}^+$)	g	1.41E+05	3.56E+03	2.61E−02	9.41E−03	5.94E−03	1.45E−03
O	(w) Salts (unspecified)	g	1.19E+06	3.22E+03	1.44E−02	9.35E−03	5.05E−03	1.44E−03
O	(w) Magnesium (Mg^{++})	g	1.71E+01	2.89E+03	1.63E+00	1.09E−02	6.15E−03	1.67E−03
O	(w) Iron ($Fe^{++}, Fe_3{}^+$)	g	2.80E+05	2.53E+03	2.52E−01	1.18E−02	7.49E−03	1.82E−03
O	(w) Strontium (Sr II)	g	2.33E+00	2.49E+03	1.12E+01	5.94E−02	9.24E−02	9.12E−03
O	(w) Suspended matter (unspecified)	g	1.08E+05	1.89E+03	5.85E+00	7.41E−02	7.79E−02	9.10E−03
O	(w) Dissolved matter (unspecified)	g	8.89E+02	1.52E+03	1.41E+02	7.90E−01	1.07E+00	5.45E−02
O	(w) Potassium (K^+)	g	5.06E+00	1.16E+03	8.27E+00	4.25E−02	6.35E−02	6.51E−03
O	(w) TOC (total organic carbon)	g	6.57E+04	4.72E+02	1.38E+01	6.37E−02	9.59E−02	9.77E−03
O	(w) COD (chemical oxygen demand)	g	2.23E+05	3.58E+02	1.44E+01	4.05E−02	8.33E−02	7.26E−04

I, input; O, output; (r), resources; (a), air emissions; (w), water emissions.

results are further processed and interpreted in terms of environmental impacts and societal preference (ISO 14040 1997).

One of the life cycle assessment methodologies is the Eco-indicator 99 (PRé Consultants 2006). The Eco-indicator 99 scores are based on an impact assessment methodology that transforms the data of the inventory table into damage scores that fall into one of seven categories: global warming (GW), ozone layer depletion (OD), photochemical oxidant creation (POC), acidification (AC), eutrophication (EU), eco-toxicity (ET), and human toxicity (HT). These can then be aggregated, depending on the needs and the choice of the investigator, into three comprehensive damage categories, or even into one single score (Goedkoop and Spriensma 2001). Therefore the Eco-indicator 99 method could be used in the creative and conceptual phases of a design process by providing a quantitative environmental impact score for each process alternative.

As defined in the aforementioned Eco-indicator 99 settings, environmental impacts were calculated in units of environmental impact (mPt), expressed in milli-eco-points, based upon the inventory analysis results. Table 3 and Figure 4 show the environmental impact of each unit process. In the results, eco-toxicity and human toxicity stand out as the environmental impact categories with the highest damage scores. Specifically, environmental impact of the cutting and welding and painting unit processes showed the highest values: 1.82E+06 mPt and 1.88E+06 mPt respectively. In the cutting and welding unit process, raw materials such as steel are a major source of environment impact. In this case, however, an alternative material cannot be substituted for steel; therefore it is very difficult to reduce the environmental impact of this particular unit process (cutting and welding). For this reason, the DFE method was applied to the painting unit process which constitutes about 51% of the overall environmental impact of forklift manufacturing. If the attachment efficiency of paint could be increased and the quantity of paint used could be reduced, then a significant reduction in the environmental impacts would be expected.

3. Application of design for environment (DFE) method in forklift manufacturing processes

Design for environment (DFE) is defined as the systematic consideration of design performance with respect to environment, health, and safety objectives over the full product and process life cycle (Ray and Guzzo 1993). By assessing environmental impact over the whole life cycle at the early development stage, DFE helps companies reduce material and energy intensity, as well as emissions and waste (Bralla 1986, Boothroyd 1994, Ishii 1994, Brezet and Hemel 1997, Stevels *et al.* 1999).

By adjusting the purpose of DFE, ISO/TR 14062 (ISO/TR, 2001), UNEP (Brezet and Hemel 1997) and major companies are presenting general guidelines for performing DFE. These references show the progress of designing environmentally friendly products by applying DFE in processes of general product development.

As stated in the previous section, we estimated that the process with the highest environmental impact value in the forklift manufacturing unit processes was the painting unit process. As a main purpose of this research, focusing on the painting unit process, we applied the DFE method which is made up of goal specification, conceptual design and detail, and manufacturing design, as described by general DFE guidelines (Fiksel 1996, Brezet *et al.* 1999).

Table 3. Results of LCIA in each process.

Manufacturing process \ Environmental category	GW	OD	POC	AC	EU	ET	HT	Total
Cutting and welding	1.15E+05	4.68E+03	1.37E+04	3.05E+05	1.07E+05	1.82E+05	1.09E+06	1.82E+06
Painting	1.49E+03	2.56E+02	5.23E+01	7.75E+03	1.57E+03	9.84E+05	8.87E+05	1.88E+06
Assembly	2.71E+01	6.64E+00	1.11E+01	1.27E+02	2.73E+01	1.64E+04	1.71E+02	1.68E+04
Test run	5.42E−01	3.43E−02	5.43E−02	1.98E+00	3.25E−01	8.49E+01	4.57E+00	9.24E+01
Repair	4.36E−01	5.46E−02	8.98E−02	1.66E+00	3.18E−01	1.29E+02	3.18E+00	1.35E+02
Shipment	0.00E+00	7.51E−02	5.27E−03	3.44E−03	2.50E−01	3.80E−02	1.30E+01	1.34E+01

Unit: mPt. GW, global warming; OD, ozone layer depletion; POC, photochemical oxidant creation; AC, acidification; EU, eutrophication; ET, eco-toxicity; HT, human toxicity; mPt, unit of environmental impact in milli-eco-points.

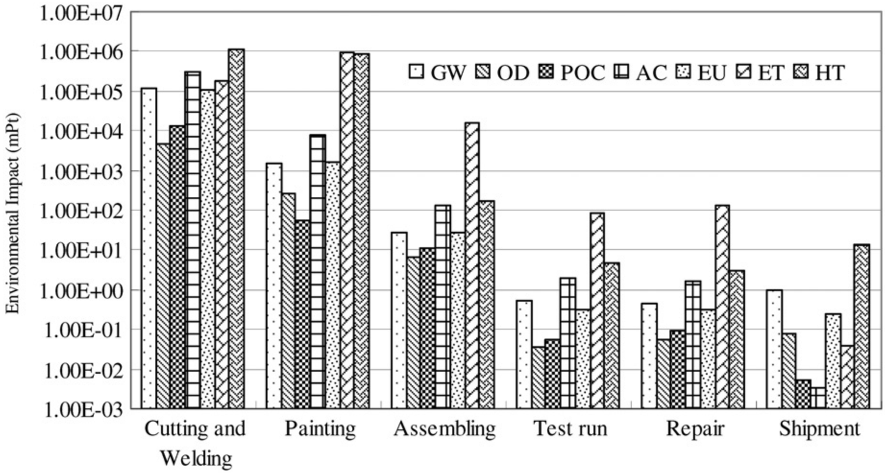

Figure 4. Environment impact contribution of each unit process to the categories. GW, global warming; OD, ozone layer depletion; POC, photochemical oxidant creation; AC, acidification; EU, eutrophication; ET, eco-toxicity; HT, human toxicity.

3.1 *Goal specification*

In the goal specification process, the focus on environmental improvement is clearly stated. For example, goals may include using more than 95% recyclable materials in a product's parts and improving the recyclability of a product by reducing the quantity of plastic parts. According to the result of LCA for forklift manufacturing processes, the primary environmental impact source in the painting process of the forklift is paint and pre-treatment material. Therefore, reducing the use of these substances was set as the goal for the DFE application.

3.2 *Conceptual design*

Once the general goals for product and process improvement are set up, then detailed plans and methods are established. In the conceptual design stage, the method for achieving the specified goal (in this case, reducing the use of paint and pre-treatment materials) is determined. Thus, two methods for reducing these materials were formulated. The first method involves making and using high solid paint. The other method requires translating from hot plate to cold plate. If hot plate is changed to cold plate, the pickling and water usage in the pickling process could be reduced.

In the forklift painting process, typically, solvent paints are used. Solvent paints are less sensitive to application conditions, which mean they can be applied over a wider temperature and humidity range. However, solvent paints are not environmentally friendly; they also have health and safety issues associated with them. To minimise the environmental impacts in painting process, a high solid paint was introduced for the forklift painting process.

High solid paints have little to no solvents in their composition. In comparison to traditional paints, these coatings have a much higher percentage of solids, around 65% to 80%. Very high solids coatings have as much as 100% solid content. Due to this increased solids content and lack of solvent, these coatings provide reduced volatile organic compound (VOC) emissions, and they have much higher viscosities, three to four times thicker, ranging around 2000 to 10,000 centipoises. Also, the thickened coating provides the advantage of fewer required coats, reducing cost per application (Lambourne and Strivens 1999, PCRC 2008).

Accordingly, in the forklift painting process, if the solvent paint is made into high solid paint by increasing non-volatile component content to 60% and by decreasing volatile component to 40%, environmental impacts and loss of paint will be reduced. The detailed information about high solid paint is given in Section 3.3.1.

3.3 *Detailed manufacturing design*

The objective of this step is to find a detailed solution to reduce environmental impacts or problems of mass production processes. The detailed manufacturing design process is the reification of the conceptual design. Thus the newly developed high-solid paint is introduced to the painting unit process in order to evaluate whether the new paint has an equal quality with existing solvent paint through experiment and assessment. In the painting unit process, the high-solid paint was determined to be a successful replacement for solvent paint. It not only reduced the negative environmental and health impacts of the forklift painting process, but also allowed the overcoat and drying sub-processes to be eliminated. A composition and property comparison of high-solid paint and solvent paint is given in the following sections.

3.3.1 *Material content and properties of developed paint*

Table 4 shows the comparison of composition of solvent paint and high solid paint. Furthermore, each chief ingredient is explained as below.

(1) *Content of resin and hardener*

Resin is an important material in determining good efficiency for coating of high solid paint. When the high solid paint was developed, the acryl ester polyol resin, which easily controls molecular weight, polarity and glass transition temperature, was used. Also, the paint solvent viscosity level and drying time by considering the spray working efficiency of paint was controlled. This was achieved by mixing a fixed quantity of high molecular weight resin.

(2) *Content of pigment*

As a pigment, carbon black could be used for painting of the forklift. When it is below 2% of the paint composition by volume, it can have the most suitable tone of colour condition. At 20–25% content level by volume, talc with low oil absorption has the best hiding power and content of solidity. Also, anti-corrosive substances added to the paint were shown to have the optimal property of matter at 5–10% level by volume.

(3) *Content of additives*

Dispersive agents cause paint particles to repel each other and stabilise them to prohibit re-cohesion. These are most suitable at concentrations of greater than 0.4% by volume. Settling agents, which can prevent sedimentation and reduces viscosity, are most suitable at concentrations of greater than 0.6% by volume.

Table 4. Comparison of the components of solvent paint with high solid paint.

Component	Type	Solvent paint (%) by volume	High solid paint (%) by volume
Resin	Polyol	12–18	20–25
Hardener	Isocyanate	2–6	5–10
Pigment	Carbon black	1.0–1.5	1.5–2.0
	Talc	15–19	20–25
	Rust preventing pigment	3–5	5–10
Additive	Dispersion agent	Over 0.3	Over 0.4
	Precipitated preventing agent	Over 0.5	Over 0.6
Organic solvent	Aromatic	25–35	15–25
	Acetate	15–20	10–14
	Ketone	6–10	3–7

(4) *Content of organic solvents*

Organic solvents dissolve the resin, give paint fluency, and increase operational efficiency of painting. The solvent paint used in forklift manufacture is made up of aromatic, acetic and ketenic compounds as a general rule. The general solvent content of paint is determined by the contained quantity of resin and environmental/work condition. Regular solvent paint contains about 60% solvent in total volume, while high solid paint contains about 40% solvent. Therefore the high solid paint can reduce by about 20% the total amount of VOCs required for painting of one forklift.

3.3.2 *Properties of the developed paint*

Properties of the high solid paint were determined by conducting a test wherein a testing board was painted with the paint developed for the forklift manufacturing process. The testing board is made from a cold rolled steel sheet ($0.8 \times 75 \times 150$ mm, KS M 5000) and treated with phosphate film. (Phosphate coatings are used on steel parts for corrosion resistance, lubricity, or as a foundation for subsequent coatings or painting.)

The paint properties were assessed as described below, with results shown in Table 5.

(1) Spray: the mixed main paint and hardening agent.
(2) Setting time: 10 min.
(3) Forced dry: 80°C, 30 min.
(4) Time for which the specimen was left at room temperature: 1 day.
(5) Property of matter assessment (the dry film thickness: $40 \pm 2\,\mu$m).

The solid content of the high solid paint is increased about 10–15% over that of the solvent paint. Drying of high solid paint occurs more slowly than with solvent paint, but no fundamental application problems were observed. Except for the slow drying time, the properties of the high solid paint are of equal quality as those of the solvent paint.

Table 5. Results of property test for solvent paint and high solid paint.

Test item	Type	Solvent paint	High solid paint	Test method
Viscosity (Ford Cup #4, sec)		24–26	26–28	ASTM D856
Solid content (%)		45–48	58–61	ASTM D2697
Drying time (min)	Set to touch	Below 10 min	Below 12 min	ASTM D1640
	Curing	Below 50 min	Below 50 min	
Gloss (60°)		16–20	16–20	ASTM D523
Adhesion		Good	Good	ASTM D3359
Flexibility		Good	Good	ASTM D522
Shock resistance		Good	Good	Du-Pont impact
Hardness		Over 2H	Over 2H	ASTM D3363
Salt spray test (5% NaCl, 240 h)	Scribed	Good	Good	ASTM D1654
	Unscribed	Good	Good	
Water resistance (20°C, 240 h)	Blistering	Good	Good	ASTM D610
	Corrosion	Good	Good	ASTM D714
	Adhesion	Good	Good	ASTM D3359
	Hardness	Over H	Over H	ASTM D3363
Oil resistance (20°C, 240 h)	Blistering	Good	Good	ASTM D610
	Corrosion	Good	Good	ASTM D714
	Adhesion	Good	Good	ASTM D3359
	Hardness	Over H	Over H	ASTM D3363
Heat resistance (80°C, 240 h)	Blistering	Good	Good	ASTM D610
	Corrosion	Good	Good	ASTM D714
	Adhesion	Good	Good	ASTM D3359
	Hardness	Over H	Over H	ASTM D3363
Acid resistance (5% H_2SO_4, 24 h)	Blistering	Good	Good	ASTM D610
	Corrosion	Good	Good	ASTM D714
	Adhesion	Good	Good	ASTM D3359
	Hardness	Over H	Over H	ASTM D3363
Alkali resistance (5% NaOH, 24 h)	Blistering	Good	Good	ASTM D610
	Corrosion	Good	Good	ASTM D714
	Adhesion	Good	Good	ASTM D3359
	Hardness	Over H	Over H	ASTM D3363

3.3.3 *Mass production test of development paint*

The high-solid paint was further tested in the actual forklift painting process of Daewoo Heavy Industries Co. Ltd in South Korea. In test applications on about 200 forklifts, the quantity of paint consumed, area of painting, working time and dry film thickness were measured. The application effects of the high solid paint are summarised in Table 6.

(1) *Operation efficiency and mass properties of the dry film in forklift painting process*

As measured by the adhesive power test (ASTM D-3359), both the solvent and high solid paint showed a satisfactory record. On the pencil hardness test (ASTM D-3363), both paints were over the 2H level. The drying time of the paint and the working efficiency were both affected by the resin and solvent content. Despite its slower drying time, the high solid paint had an equal working efficiency as the regular solvent paint. Also, the high solid paint reduced spray painting time by about 4%.

(2) *Quantity of consumed paint*

After the painting process, the average thickness of dry film was controlled to be $40 \pm 5\,\mu m$. For painting one forklift, 15 litres of solvent paint was required, whereas just 12 litres of the high solid paint was used. Therefore, use of high solid paint allows 25% more surface area to be covered with the same paint quantity and a concurrent 20% reduction in paint usage.

(3) *Volume of VOC*

The solid content in the developed forklift paint was increased from 45% (in solvent paint) to 56%. When the high solid paint was compared with solvent paint, the volume of VOC used was reduced by about 11% at the same volume of paint used. Also when this was applied to real production processes, the paint usage was reduced by 20% per one forklift. As a result, there was an overall reduction effect of 32% in the overall volume of VOC used.

(4) *Generation of paint sludge*

Some of the VOC elements in the spray painting process are volatilised and the others remain as paint sludge. Consequently, the quantity of paint sludge originating in the painting process is affected by the solid content. In the process of painting one

Table 6. Application effects of high solid paint at Daewoo Heavy Industries Co. Ltd in South Korea on approximately 200 forklifts.

Type Line test	Solvent paint	High solid paint
Average quantity for application (L/forklift)	2.0	1.6
Spreading rate (forklift/L)	0.5	0.6
Average thickness drying film (µm)	45	45
Average thickness wet film (µm)	100	80
Solid volume ratio (%)	45	46
Working hour (min/forklift)	2.5	2.4

forklift, 6.3 litres of paint sludge was produced by solvent paint, whereas just 5.0 litres of paint sludge remained after using high solid paint. Therefore, when the high solid paint is applied in the actual production line, the total amount of paint sludge is expected to decrease about 20%.

3.3.4 *Environmentally sound production process for forklift*

If the high solid paint is applied in the painting unit process, both overcoat application and drying can be omitted from the painting unit process as shown in Figure 5. Because the solvent paint has a low solid content, it cannot produce a 55 μm-thick layer in one coat. So, it has to have both a primary coating and an over coating process in order to create satisfactory paint thickness. However, in the case of the high solid paint, a single paint application of 55 μm thickness is possible without the overcoat and drying processes.

A LCA was performed on the forklift painting unit process based on use of the high solid paint. Figure 6 shows the environmental impacts from the painting process using both solvent paint and high solid paint. The results show that solvent paint has an eco-toxicity of 9.84E+05 mPt and a human toxicity of 8.87E+05 mPt. In case of painting

Figure 5. Two omitted processes in painting process flow when high solid paint is applied in the painting process.

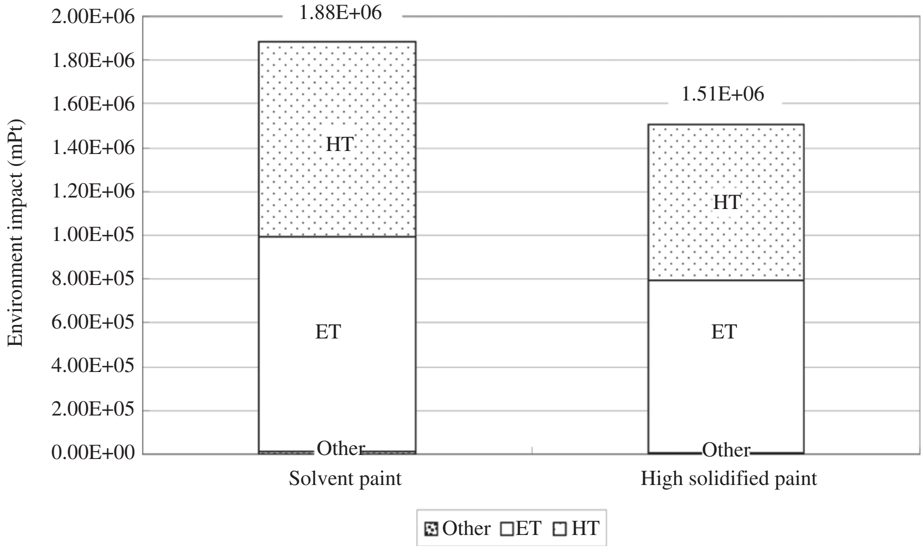

Figure 6. Comparison of environmental impact of forklift painting process using solvent paint and high solid paint.

process using high solid paint, eco-toxicity represented 7.88E+05 mPt and human toxicity was 7.10E+05 mPt. As shown in Figure 6, eco-toxicity and human toxicity contributed about 99% of the total environmental impacts. In more detail, cadmium (Cd), lead (Pb), mercury (Hg), and nickel (Ni) from paint production were main the contributors to eco-toxicity and human toxicity. Therefore, the use of high solid paint could reduce overall environmental impacts of the forklift painting unit process by about 20%: from 1.88E+06 mPt to 1.51E+06 mPt.

4. Conclusions

In this study, LCA and DFE methods were applied to design a more sustainable manufacturing process for forklifts. Using these methods, high solid paint was developed to replace solvent paint, and the painting unit process was redesigned. By incorporating the high solid paint in an actual manufacturing process, the environmental impact was demonstrably reduced.

As shown by an LCA of the forklift manufacturing process as a whole, the environmental impact for the eco-toxicity and human toxicity were most significant. Among the manufacturing processes, the cutting and welding process (54%) and painting process (45%) had the greatest negative impacts. However, in the cutting and welding process, the major source of environmental impacts is due to the use of steel. However, since steel is the basic raw material of the forklift, it cannot be replaced with a substitute material. Therefore, in this study, environmental impact was reduced via the painting unit process. A high solid paint was developed by increasing the solid content of the solvent paint beyond the content in existing paints. This high solid paint allowed the omission of the overcoat and drying process from the forklift manufacturing requirements. Also, the paint could have diminished environmental impact due to reduced VOCs use. As a result, the environmental impact was reduced by about 20% in the painting unit process and about 11% in the overall manufacturing process.

The LCA and DFE tools are not only fundamental for process enhancement and development of components, but also enable designers to create or redesign products by taking into account environmental issues. However, further evaluation methods such as financial effects and material availability may highlight additional benefits not included in the analysis. For development of environmentally friendly products and processes, a total cost analysis could be a useful evaluation method for economic issues. Within a total cost analysis method, the operating costs, raw and ancillary materials costs, and pollution abatement costs could be considered for determination of cost effective manufacturing processes. By combining LCA and DFE with economic analysis methods alternatives that minimise both cost and environmental impact for sustainable manufacturing process and products can be identified.

The analysis and redesign project discussed herein focused only on the forklift painting unit process in order to reduce environmental impacts. If applied to the other manufacturing unit processes, more sustainable manufacturing processes and products could be expected.

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Note

1. ISO is the International Organisation for Standardisation. It is made up of national standards institutes from countries large and small, industrialised, developing and in transition, in all regions of the world. ISO develops voluntary technical standards which add value to all types of business operations. ISO standards raise levels of quality, safety, reliability, efficiency, effectiveness, compatibility and interchangeability and provide such benefits at an economical cost (ISO, 2008).

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