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ECO-EFFICIENCY ANALYSIS OF PLASTICS USED IN ELECTRICAL EQUIPMENT MATERIALS:
COMPARISON OF PBT AND PHENOLIC RESIN IN CIRCUIT BREAKERS

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Abstract

Plastics are materials that are increasingly being used in the electrical and electronic industry. However, due to this recent demand, the amount of waste generated from electric and machinery has reached 14.8% of the total plastic waste in Japan in 1998. In this study, an eco-efficiency analysis comparing polybutylene terephthalate and phenolic resin in the production of circuit breakers is performed. While PBT showed 4% better environmental performance than phenolic resin, this latter has showed an economical advantage of 13%. Mechanical recycling and incineration with energy recovery proved to be better solutions than simply landfill, improving the eco-efficiency performance by a range of 2-3%.

KEYWORDS: *Ecodesign, Eco-efficiency, Plastics, Electrical Equipment*

1. Introduction

Since the creation of Agenda 21 at the 1992 Earth Summit, sustainability has become a priority in order to avoid the increasing environmental threats to global development. In order to achieve this goal society, business and government have to make use of some strategies and tools.

In recent years, plastics have become a key to innovation in the electric and electronic industry. They are selected due to their performance benefits and efficient use of resources: weight reduction, miniaturization and electrical and thermal insulation [APME, 2001]. Nevertheless, in 1998, 9,840,000 tons of plastic waste was generated [METI, 1998] with electric and machinery contributing to 14.8% of the total. Based on these numbers and the challenge of sustainable development, a more effective use of plastics is clearly necessary.

Among the plastics sold into the electrical and electronic sector, phenolic resins proved to be one of the most popular plastics from the thermosetting group, with a production of 261,513 ton in 2000 and growing at a rate of 4.6% per year. In the thermoplastic group, Polybutylene Terephthalate (PBT) is one of the fastest growing plastics in the market, with a production of 72,901 ton in 2000 and

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growing at a rate of 14.6% per year [Plastics Age Co., 1999]. Due to increasingly strict environmental laws, it is assumed that environmental factors are highly contributing to such a change. In order to verify this hypothesis, as well as to study the economical factors involved, an eco-efficiency analysis for these two plastics was performed. The analysis includes all relevant steps of the process, from plastic production to its disposal or recycling.

With this analysis, it is possible to identify the strengths and weaknesses of the plastics studied. Environmental impacts, as well as cost impact factors, also provide clues for an optimization of the process. At last, variation of the process is checked in six different scenarios.

This eco-efficiency study is targeted towards decision makers, plastic research groups for PBT and phenolic resin, electrical equipment producers, scientists, consumers and other relevant parties.

1.1. Functional Unit

Considering the wide variety of electrical products and in order to quantify this analysis, a case study is selected. The functional unit is the reference unit used for all life cycle balances [JEMAI, 1999]. In this study, it is defined as follows: 'production of the housing of 1 unit of circuit breaker'. Circuit breakers are instruments present in all sectors of society and their housing is constituted of plastics.

1.2. Scope of the study

The work is done on the national level of Japan. It does not treat local and regional particularities that possibly have an influence on the analysis. The results refer to the use of PBT and phenolic resin in the production of circuit breakers. The results are also valid when these plastics are used in the production of other electrical equipment that has the same specifications as circuit breakers. The extension to other applications with different technical and quality specification is not valid.

It is restricted to the ecological valuation of the present essential aspects of the environmental impact. It therefore does not include estimation of possible effects or influences that new technologies may bring about.

2. Methodology of eco-efficiency analysis

The methodology applied to this work is the eco-efficiency analysis developed by the chemical company BASF AG [BASF AG, 2000]. Eco-efficiency analysis is an instrument for the comparative assessment of products or process alternatives in order to achieve sustainable development. Here, two of the three pillars of sustainable development - Ecology and Economy - are assessed and set in relation to each other. It is a product-oriented tool.

In a 'traditional' environmental management system, the focus is put on the production and its environmental impacts. But according to Schmidt *et al.*, 2001, and others that put focus on products [e.g. Oosterhuis *et al.*, 1996], besides reducing the accumulated environmental impacts, product oriented company environmental work provides competitive advantages in the eco-conscious markets, larger knowledge of the products, more complete basis for documentation in relation to customers and authorities, better coordination and cooperation across the company and a closer dialogue with suppliers and customers.

The analysis is based on an extended balance of environmental influences (eco-balance according to ISO 14040 series) and the total costs of all considered modules inside the defined system boundaries, which include all relevant steps of the plastic production and its disposal. The results of the environmental and cost analysis are summarized and compared so that the eco-efficiency of the process alternatives can be determined and presented in an eco-efficiency portfolio.

3. Inventory Analysis

3.1. System boundary

Based on the plastics in study, the operations related to their production, processing and final disposal or recycling are considered. A simplified representation of the system boundary is represented in Figs. 1 and 2. About the system boundary, it can be said that:

1. The life cycles of all main system components – required for the production, processing and disposal of these plastics is investigated [Ulmann, 1992].
2. Energy supply and consumption data in the Japanese power supply are considered.
3. Generic unit operations such as transportation are simplified, based on the distance between manufacturing plants and distributors, using a 16-ton truck.
4. Incineration, final disposal (landfill) and recycling of wastes are considered for Japan only.
5. Products or processes with no significant impacts or no adequate data are discarded.
6. Emission standards are considered in a national level (Japan).
7. Since plastics are the objective eco-efficiency analysis, different aspects in the production, processing and disposal of the plastics are considered. Identical steps in all mentioned phases for both plastics, which do not enable any basis for comparison or do not have considerable influence on the results, are not considered.

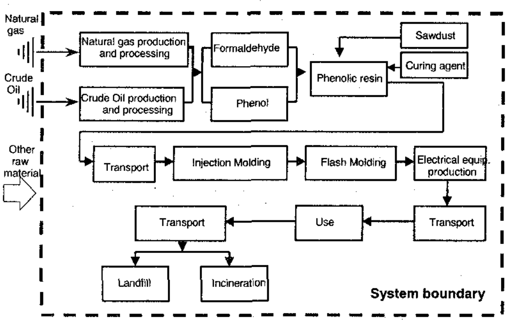

Fig. 1 – System boundary for phenolic resin

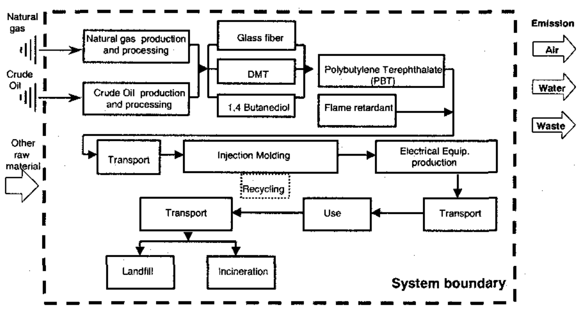

Fig. 2 – System boundary for PBT

3.2. Data acquisition and quality

For the environmental profile of each module of the system boundary, a life cycle inventory database, 'The Boustead Model for life cycle inventory calculations' (Version 4.2 for Windows 95/98/NT, 2000) was used [Boustead, 2000]. Moreover, whenever possible, site-specific information directly provided by producers was used. Data related to the production process, material and energy consumption of 1 unit of circuit breaker belong to this group of data. Information for the evaluation of toxicity potential was based on chemical databases as well as specific literature. Information about cost of production and processing was obtained from experts from the industries involved. Suggestions from experts as well as self-assumptions were applied in the risk potential analysis due to lack of available data.

3.3. Assumptions for base case

Table 1 shows the base case assumptions. The composition of the plastics used in the electrical and electronic industry is common to different electrical devices. However, the number of cycles/hour in the processing phase varies according to the amount and type of material injected in the mold.

For the production of a circuit breaker, the amount of phenolic resin used is: 7 g in the plate, 80g cover and 140 g base, with a wall thickness of 2.75 mm. The weight is then obtained by the product of the density and the volume of the circuit breaker. Having established the amount needed, characteristics of the injection molding is determined. As a base case, landfill was considered as disposal way, because it represents the common practice in the majority of the cases. Later, in different scenarios, other disposal ways were analyzed.

Table 1 – Assumptions for base case

	PBT (30% fiber glass)	Phenolic resin
Density (g/cm ^{3})	1.66	1.45
Weight (kg)	0.213	0.227
Thickness of the wall (mm)	2.25	2.75
Additives (% w/w)	10% Flame retardant (Decabromodiphenyl oxide)	48 % Wood flour 4% Hexamethylene tetramine
Losses (% w/w)	5%	20%
Processing	Injection Molding	Injection Molding
Cycle time	144 cycles/ h	100 cycles/h
Number of molding parts	2	2
Energy consumption	0.32 MJ	0.98 MJ
Disposal	Landfill	Landfill

3.4. Results of inventory analysis

Based on the defined system boundary and assumptions, the inventory analysis was carried out. The final result for both plastics, considering all steps in their life cycle, are used as input for the impact assessment (Table 2). Negative values represent a credit gained in the process due to the recovery of material or recirculating flows along the life cycle of the object in study. In the case of PBT, energy is recovered in the production of flame retardant. The excessive use of bromine produces large amount of energy that can be recovered for steam production.

Table 2 – Inventory for production of housing of 1 unit of circuit breaker

Inventory data		PBT 0.213 kg	Phenolic resin 0.227 kg	Inventory data		PBT 0.213 kg	Phenolic resin 0.227 kg
Raw material				**Air emission**			
Water	kg	42.7	2.55	CO_2	mg	8.29E5	4.43E5
Coal	kg	0.06	0.04	SO_x	mg	5.61E3	3.14E3
Oil	kg	0.12	0.08	NO_x	mg	1.41E4	3.53E3
Gas	kg	0.30	0.14	CH_4	mg	1.52E4	3.24E3
Lignite	kg	0.04	0.01	NM-VOCs	mg	1.63E3	854.79
Limestone	kg	0.00	0.00	Halogen	mg	0.42	0.45
Bauxite	kg	0.00	0.00	NH_3	mg	90.15	12.45
Sulphur	kg	0.00	0.00	N_2O	mg	0.33	0.60
NaCl	kg	0.05	0.09	HCl	mg	37.44	18.57
KCl	kg	0.00	0.00	**Water emission**			
Feldspat	kg	0.01	0.00	COD	mg	76.96	72.82
Sand	kg	0.12	0.14	BOD	mg	7.53	8.21
Electricity consumption				Nitrogen	mg	1.48	15.69
Coal	MJ	1.64	1.08	NH_4	mg	9.86	19.75
Oil	MJ	5.42	3.50	PO_4	mg	2.72	28.05
Gas	MJ	14.57	7.05	AOX	mg	0.00	0.33
Hydro	MJ	0.06	0.00	Heavy metals	mg	1.20	0.39
Nuclear	MJ	1.70	1.41	Hydrocarbon	mg	5.89	4.24
Lignite	MJ	0.67	0.11	SO_4	mg	431.68	789.91
Biomass	MJ	-1.76	1.33	Cl^-	mg	1.86E6	2.72E3
Others	MJ	-0.37	-0.27	**Waste**			
Total	MJ	21.93	14.22	Domestic	kg	0.01	0.01
				Special	kg	0.00	0.00
				Building rubble	kg	0.12	0.09

4. Impact Assessment

The results of inventory analysis were then applied to evaluate the environmental impacts. Categories considered are: (1) energy consumption; (2) material consumption; (3) emissions (to air, water and land); (4) toxicity potential; (5) risk potential and (6) area demand.

4.1. Energy consumption

Energy consumption was determined over the entire life cycle as primary energy consumption. To calculate the total energy requirements, the upper heating value of the primary equivalents is used. These quantities are summed up and measured in MJ/functional unit. Figure 3 shows that the sole production of PBT is higher than the whole energy consumption of phenolic resin, despite the latter's higher energy consumption during processing (injection molding). PBT has energy consumption approximately 54% higher than phenolic resin case. This is explained by the different reaction paths and, as a consequence, different characteristics of the processing of these plastics. It reflects how important the chosen reaction path to produce the polymer is.

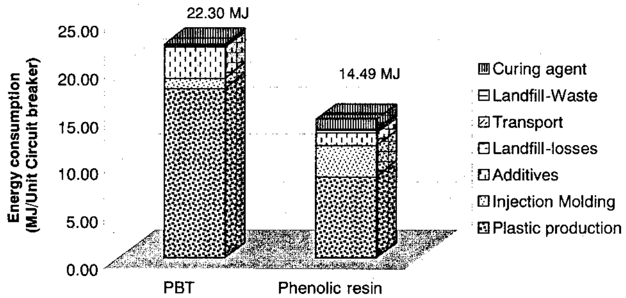

Fig. 3 – Energy consumption along life cycle of PBT and Phenolic Resin

4.2. Material consumption

Table 3 – Reserve factors

Raw material	Resources [years]	Characterization factor	
Coal	160	6	[b]
Crude oil	42	24	[b]
Natural gas	63	16	[a]
Lignite	387	3	[a]
Limestone	200	5	(estimated)
Bauxite	200	5	[a]
Sulphur	53	19	(estimated)
NaCl	1000	1	(estimated)
KCl	336	3	(estimated)
Feldspat	1000	1	[a]
Sand	1000	1	[a]

[a] U.S. Geolgical Survey, Mineral Commodity Summaries, 1997

[b] Römpp Chemie Lexikon. Thieme. Stuttgart Vol. 5, page 3914

The raw material consumption recorded in the material balance is weighted according to the estimated time of availability of the respective reserves (Table 3). Evaluating the individual materials in terms of their years of reserves produces factors for weighting the individual mass streams. These factors are calculated in: 1000/ years of reserve.

Renewable materials, when sustainable managed, are considered to have an infinite long availability and therefore they receive a factor of 0.

Despite of the higher production losses in the case of phenolic resins, both materials have almost the same level of material consumption, with only 5% higher consumption in the case of PBT (Fig. 4). On the one hand, the use of halogenated flame retardant improves flammability characteristics of PBT, but its production requires relevant amounts of material and energy.

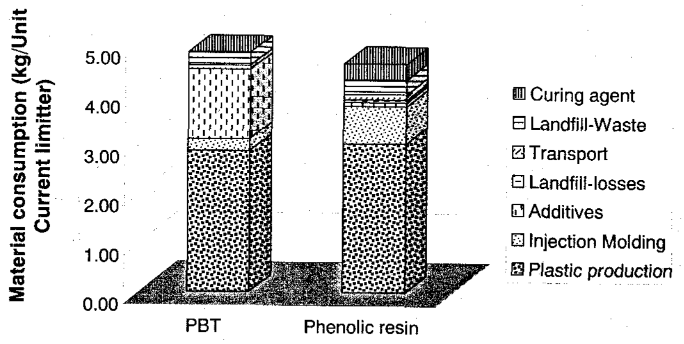

Fig. 4 – Material consumption along life cycle of PBT and Phenolic Resin

4.3. Emissions

4.3.1. Air emissions

The assessment of air emissions is carried out according to four effect categories:

- Global warming potential (GWP), [CO_2 equivalent]
- Ozone depleting potential (ODP), [R11 equivalent]
- Photochemical ozone creating potential (POCP), [Ethene equivalent]
- Acidification potential (AP), [SO_2 equivalent]

The results are measured in the respective substance equivalent/customer benefit.

Table 4 – Impact potential of the air emissions

Substance	GWP [CO_2 equivalent]	ODP [R11 equivalent]	POCP [Ethene equivalent]	AP [SO_2 equivalent]
CO_2	1			
SO_x				1.00
NO_x				0.70
CH_4	11		0.007	
NM-VOC			0.416	
Halogen. HC	4500	1		
NH_3				1.88
N_2O	270			0.88
HCl				

Source: Heijungs, R. *et al.*, *Environmental life cycle assessment of products. Guide,* Leiden, October, 1992;

The GWP category reflects the same distribution observed in the primary energy consumption. In the ODP category, no significant difference was presented by either plastic. Since the main sources of the ODP are halogenated hydrocarbons, the contribution of the flame retardant in PBT's case to this impact category is considerable. Due to the SO_2 emissions, the impact of the flame retardant production to the AP category is also high. POCP is caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of light and nitrogen oxides (NOx). For the production of plastics crude oil is used. Through the crude oil production and processing VOC-emissions are discharged, influencing this category (Figs. 5, 6, 7 and 8).

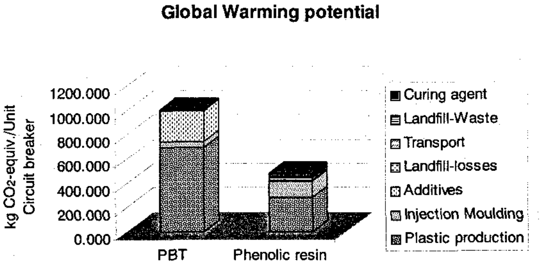

Fig. 5 – Global warming Potential

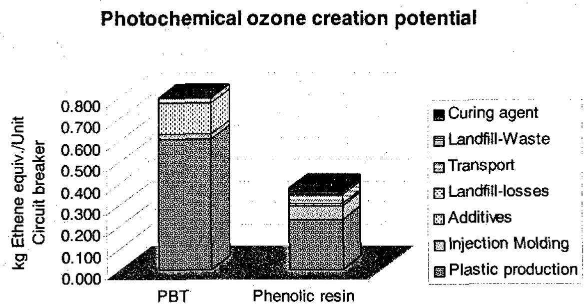

Fig. 6 – Ozone depletion potential

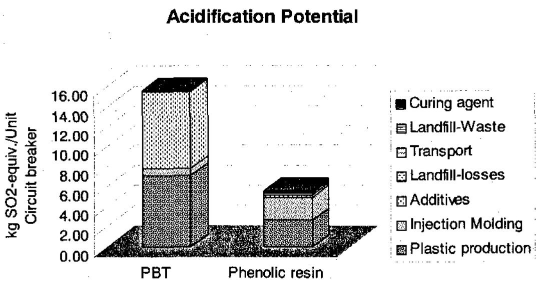

Fig. 7 – Acidification potential

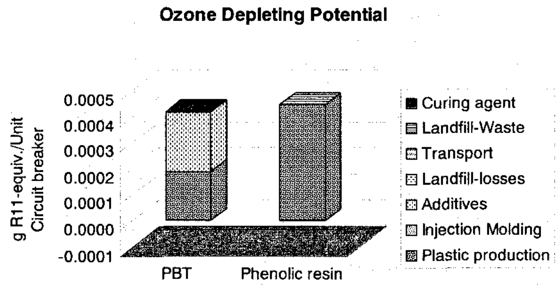

Fig. 8 – Photochemical ozone creation potential

4.3.2. Water emissions

Water emissions are calculated as critical volume, already described by the SAEFL, 1998. The limits used for the respective emission to water are the limits listed in the wastewater regulations, the Japanese National Effluent Standard (Ministry of Environment). The critical volumes are subsequently summed up and normalized. Considering the life cycle of both plastics, Fig. 9 shows that PBT has a water emission impact 43% higher than phenolic resin.

Table 5 – Arithmetic values for impact potentials in case of emissions to water

	General specification for waste water	Dilution factor applied in the calculation of the critical volume
COD	120 mg/l[1]	0.008
BOD	120 mg/l[1]	0.008
N	60 mg/l[1]	0.017
NH_4	60 mg/l[1]	0.017
PO_4	80 mg/l[1]	0.013
AOX	1 mg/l[2]	1.000
Heavy metals	0.1 mg/l[1]	10.000
Hydrocarbons	0.1 mg/l[1]	10.000
Cl^-	1000 mg/l[3]	0.001
SO_4^{2-}	1000 mg/l[3]	0.001

Source: 1 National Effluent Standard – Japan; 2 German Sewage Decree; 3 Carbotech AG

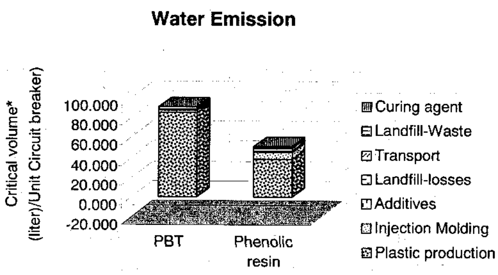

Fig. 9 – Water emission along life cycle of both plastics

4.3.3. Wastes

Wastes are classified into three main categories: special wastes, domestic waste and building rubble. As can be seen at Fig. 10, the simple landfilling of the wastes, with no recovery of the losses or final products, only increases the waste impact on the environment, representing 27% of the total PBT solid waste (0.009 kg) and 22% (0.010 kg) in the case of phenolic resin. A negative value, in the case of PBT, is indicative of the amount of solid waste avoided by the recovery of energy in the production of flame retardant.

Tab. 6 – Arithmetic value for solid waste

Wastes	Factors
Special waste	5
Domestic waste	1
Building rubble	0.2

Source: Saling *et al*, 2000

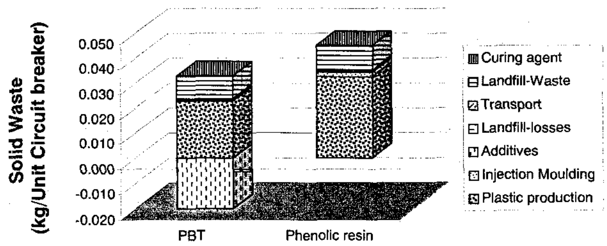

Fig. 10 – Solid waste

4.4. Toxicity potential

Each hazardous material occurring during the manufacture-, use-, and disposal of products is recorded quantitatively for the determination of the toxicity potential. The hazardous materials are weighted according to their labeling. These weighting factors are logarithmically graded (LD_{50} values).

Tab. 7 – Assessment parameters for toxicity potential

Harzard symbol	Limit concentrations (LD_{50}-value, rat, oral)	Weighting factor
Xi: irritant		1
C: corrosive		10
Xn: harmful	200 mg/kg < LD_{50} ≤ 2000 mg/kg	10
T: toxic	25 mg/kg < LD_{50} ≤ 200 mg/kg	100
T+: very toxic	LD_{50} ≤ 25 mg/kg	1000

Source: Saling *et al*, (2000, not published)

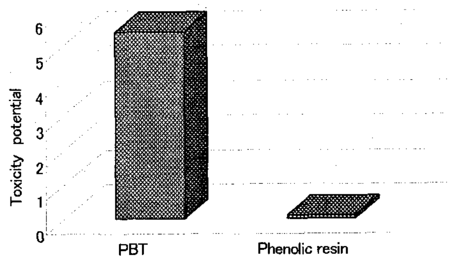

Fig. 11 – Toxicity potential

4.5. Risk potential

The approach adopted here is similar to a risk assessment in the case of plant safety in that the probability of occurrence and the level of damage are estimated. For this specific case, characteristics of the process (temperature and pressure), level of exposure (TLV), handling, features of the product, transportation and disposal were analyzed. Although the production phase involves a higher number of risks, the use phase for such electrical equipment materials has a longer lifetime than production. Therefore, both the production and use phase, are equally weighted.

Tab. 8 – Risk potential

	Factor	Risk	Risk potential		Weight
			PBT	Phenolic resin	
Production phase	High temperature	Body injuries	3	2.2	40%
	Exposure	Volatiles compounds	1	3	
	Handling	Injuries in handling (direct contact, material preparation, etc.)	1	3	
		Total	2	3.28	
Use phase	CTI Index	Fire	1.5	2	40%
		Total	0.6	0.8	
Disposal phase	Transportation	Car accidents	1	1	20%
	Landfill	Deposition	1	1	
		Total	0.4	0.4	

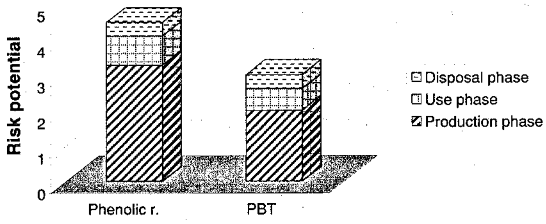

Fig. 12 – Risk potential in production, use and disposal phase.

4.6. Area demand

In this study, the chemical industry and the natural land used for wood growing/harvesting had the largest contribution on area demand. Nevertheless, due to the fact that sawdust normally comes as a recycled product from the furniture industry, the consideration of the natural land for wood is still a point of discussion.

In the case of chemical industry, the area demanded for production of 1 kg of plastic is given by Dittrich-Kraemer, 2001 and it is equal to 0.005 m^2. For the sawdust, the calculation procedure used was:

$$\text{Volume of wood per hectare generated at cutting} = \text{Growing rate} \times \text{Time for cutting} = [m^3/ha] \quad (1)$$

$$\text{Volume of wood per circuit breaker} = \frac{\text{kg wood/circuit breaker}}{\text{Density}} = [m^3] \quad (2)$$

$$\text{Area demand} = \frac{\text{Volume of wood per circuit breaker}}{\text{Volume of wood per hectare generated at cutting}} = [ha] \quad (3)$$

Resulting in a total area demand of 0.008 m^2/kg for PBT and 0.013 m^2/kg for phenolic resin.

4.7. Weighting

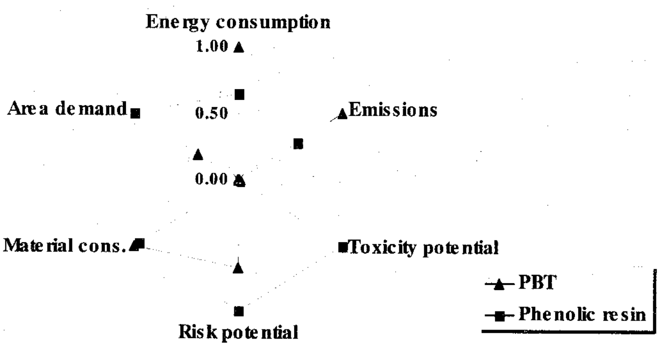

Fig. 13 – Eco-fingerprint

These categories are then drawn into a polygon with 6 axes (Fig. 13). First, the results of the impact assessment are normalized to a scale from 0 to 1, where the least favorable alternative is assigned to 1. The rating of the other alternatives is done relatively to it.

Phenolic resin and PBT both each represent the worst position in three of the six axes of the eco-fingerprint. Phenolic resin has just a slightly worse performance due to the fact that in the case of materials consumption, both present similar impacts, with only 5% higher consumption for PBT. Next, a weighting step is unavoidable in order to obtain a single index for all environmental effects, namely all categories must be combined and considered. This is done using two different schemes: the relevance factors and societal weighting factors [BASF AG, 2000]. The relevance factors measure the 'importance' of the results of an effect category in comparison to that of the other categories. Their calculation is based on the method of the specific contribution, where the results of the impact assessment are compared with unified reference values of the period under consideration. These values come from published values for the total emissions in the space studied, in this case Japan, and must therefore be considered objective factors. They are recalculated for each analysis (Figs. 14 and 15).

The societal weighting factors express how dangerous the different environmental problems are assessed by the public. They are determined through surveys, public opinion poll, expert interviews, etc.

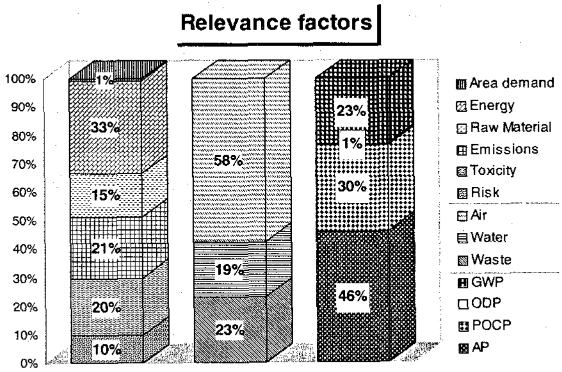

Fig. 14 – Relevance factors

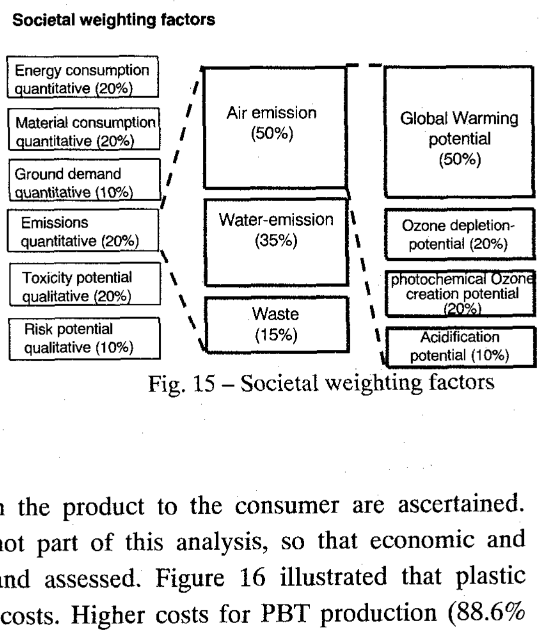

Fig. 15 – Societal weighting factors

4.8. Costs

All costs which arise directly or indirectly from the product to the consumer are ascertained. Avoidance costs or other costing approaches are not part of this analysis, so that economic and ecological impacts may be separately computed and assessed. Figure 16 illustrated that plastic production represents the greatest load to the total costs. Higher costs for PBT production (88.6% higher than phenolic resin) could be explained by relative smaller market in comparison to phenolic resin as well as the more complex processing needed, a fact already demonstrated by the higher material and energy consumption.

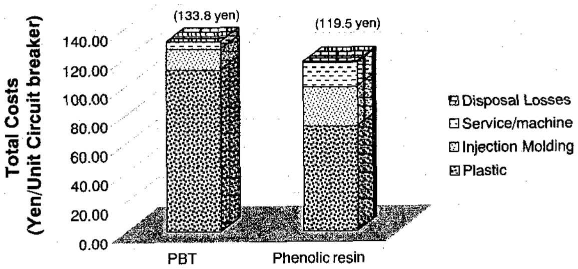

Fig. 16 –Total costs along the life cycle of both plastics

5. Results of base case

By combining the costs and the environmental impacts, we obtain the final result of the eco-efficiency analysis, showed in the portfolio presented below (Fig. 17). The axis of the environmental impact and costs are inversely drawn. Thus the most favorable alternatives are located top right in the portfolio, the least favorable ones in the bottom left. It can be seen that PBT has slightly better environmental performance than phenolic resins by an advantage of 4%. On the other hand, the latter has 13% better economical performance than the former. As they are both in the same diagonal, it can be said that the environmental advantages of one plastic is compensated by the economical advantages of the other plastic, therefore both presenting similar eco-efficiency.

As presented in Fig. 13, differences in the energy consumption of both plastics and emissions discharged to air, water and land were balanced with the differences in area demand and toxicity potential, having in total a similar environmental impact. Costs, in their turn, have as their main factors the plastic production and processing (molding) costs. Additionally, in the total costs, no remarkable differences between these two plastics were noticed.

Nevertheless, it must be remembered that although both of them presented similar results, neither had a high eco-efficiency, represented by a top right position in the portfolio. Therefore, ways to improve these results should be studied. Based on the main factors pointed to in this base case, six scenarios are built.

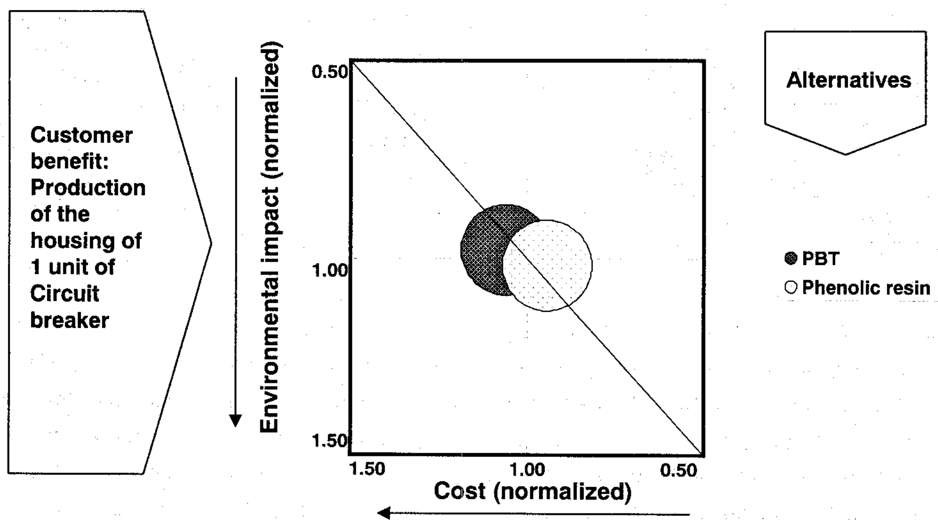

Fig. 17 – Eco-portfolio of the base case

6. Results expected in six scenarios

The calculations of the eco-efficiency analysis were based on the basic assumptions done at the beginning of the analysis. In order to check how the eco-efficiency changes when some frame conditions vary, 6 scenarios were considered. They were selected based on the main critical factors of the base case analysis: energy consumption, material consumption and costs.

6.1. Scenario 1: 'Incineration case'

Here, a change from landfill to incineration with energy recovery is analyzed. As shown in Fig. 3 and Fig. 13, energy plays a very important role in this process, representing a relevance load of 33%. (Fig. 14). In order to reduce this impact, one possibility would be the recovery through incineration, analyzed in this scenario (Fig. 18).

Despite of the energy recovery, incineration still only deals with the losses in the process. Considering a higher heat value (26.9 MJ/kg in comparison to 24.5 MJ/kg for PBT) as well as higher loss rate (20%) in the case of phenolic resin, its better performance is already expected. In numbers, an energy recovery of 33.7% higher than PBT is obtained by phenolic resin and an improvement of 2% on phenolic resins' eco-efficiency was observed.

6.2. Scenario 2: 'Recycling of PBT pre-consumer wastes'

Since recycling of pre-consumer wastes is an option that has been implemented during the last years, its effect in the eco-efficiency performance is evaluated. Nevertheless, although the mechanical recycling of phenolic resin is technically possible [Matsumoto, 1997], it is still only practiced in laboratory scale. Post-consumer wastes, due to impurities of other materials, are more difficult to be recycled. Those were considered to be disposed in landfills, since it reflects the present situation in Japan. With material recovery, improvements not only in environmental impact, but also in terms of costs are observed. Losses are reused and a lesser amount of raw material needs to be consumed in the input side. As a consequence, less energy is also required. Comparing both plastics (Fig. 18), environmental advantages are clearly seen in the case of PBT. In terms of costs, even with less production cost for PBT as well as no cost for disposal of pre-consumer wastes, phenolic resin still presents slight advantages. In total, an improvement of 3% in the eco-efficiency of PBT was observed.

6.3. Scenario 3: 'Recycling and incineration'

This scenario is a combination of the two discussed above. With improvement of phenolic resin performance by incineration and mainly by recycling in the case of PBT, the final result is almost the same for both plastics, either in the environmental side or in the cost impact side. Therefore, it can be said that their eco-efficiency is practically the same yet still not optimal, since both circles are not in the top right position in the portfolio (Fig. 18).

6.4. Scenario 4: 'Reduction in production losses (Phenolic resin)'

Since the recycling of pre-consumer wastes of phenolic resin is still in a development process, the objective in this scenario is to check how the eco-efficiency performance change if the loss rate in the production process reduces from 20% to 10% and how effective the implementation of such project would be.

Figure 18 shows that with only 10% reduction in the pre-consumer waste of phenolic resin, its eco-efficiency performance changes considerably, improving its environmental performance in 5%.

Although methods of how to produce this reduction are out of consideration here, making use of this eco-efficiency instrument, it can be seen that improvements in the present system have bigger eco-efficiency effect than simply changes on the disposal ways.

6.5. Scenario 5: 'PBT cost reduction'

As showed in the cost impact evaluation (Section 4.8), PBT costs are much higher (88.6%) that of phenolic resins. Taking the energy consumption as an indicator for costs, a scenario is built considering PBT costs 35% higher than phenolic resin, since this is the difference presented in this impact category.

As shown in Fig. 18, it confirms that cost is a key factor for PBT. With the environmental advantages already presented in the base case and a cost reduction, PBT turns out to be the highest eco-efficient alternative. It is clear that plastic costs cannot be simply be based on the energy factor, but this portfolio shows that such cost reductions are of extreme relevance to its eco-efficiency performance. In this case, it presented an improvement of 11%.

6.6. Scenario 6: 'Alternatives to sawdust consumption rate'

Sawdust is a very common additive used in the production of phenolic resins aimed for the production of electronic and electrical equipment. In this scenario, alternatives to the base case rate (48% of sawdust) are tested: 40%, 45% and 52% (Fig. 18).

The higher the sawdust rate, the lower is the impact on the environment. This is due to the fact that in the case of wood, no chemical process is involved, costs are lower and this material comes usually from the wastes of the furniture industry. Nevertheless it must be remembered that, since sawdust is used as an additive, its rate in the phenolic resin formulation is limited.

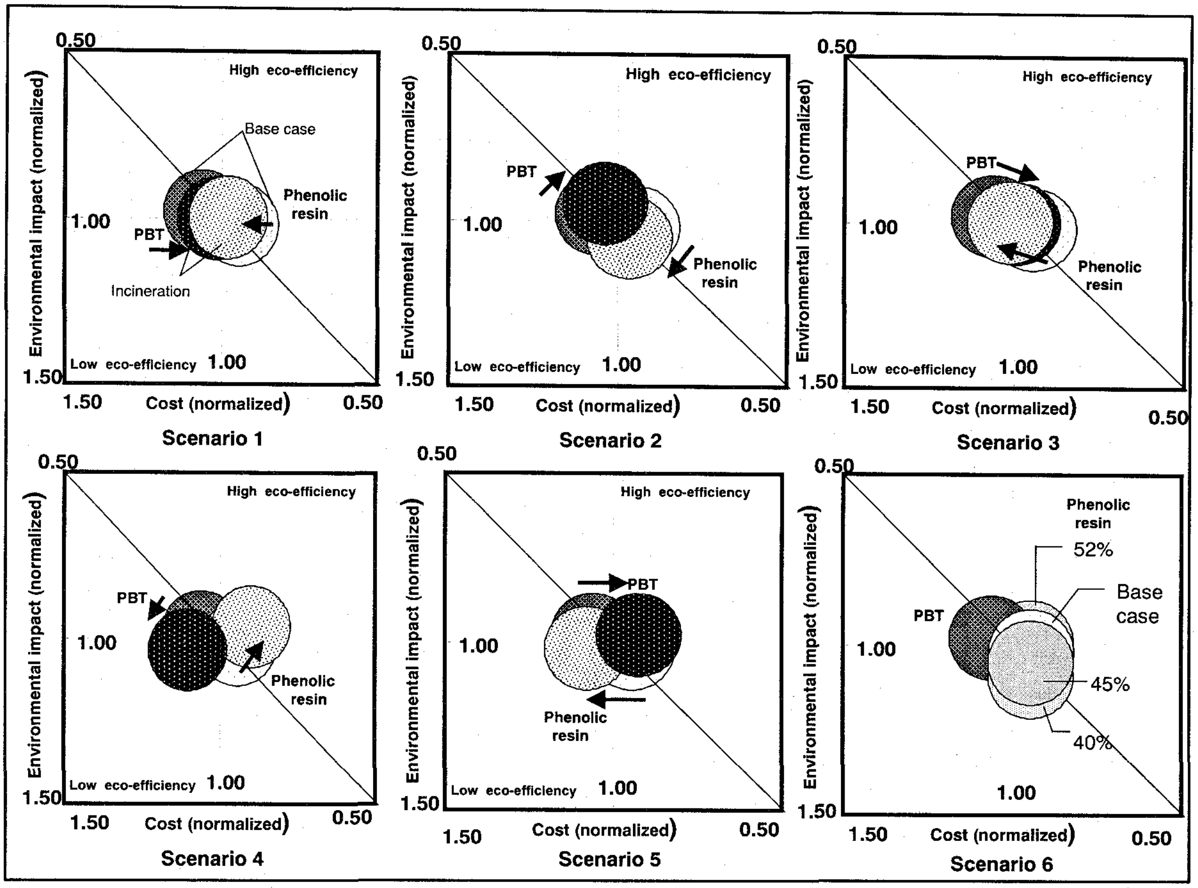

Fig. 18 – Results of performance in scenarios

7. Conclusions and Recommendations

7.1. Conclusions

Among plastics, phenolic resins prove to be one of the most popular plastics from the thermosetting group. Its market has been affected by the increasing strict environmental laws, and others polymers such as polybutylene terephthalate (PBT) are gaining market.

While PBT has presented 4% better environmental performance than phenolic resin, the latter has shown 13% better economical performance. Due to their position in the portfolio, it can be said that both present similar eco-efficiency. From the environmental side, the impacts on material and energy consumption proved to be the critical factors. Since emissions are directly connected with these two factors, a high load of this impact could be already expected. From the economical side, plastic production presented to have the greatest load, with PBT presenting 88.6% higher costs than phenolic resins. Higher costs for PBT could be explained by the more complex processing needed as well as its relatively smaller market in comparison to phenolic resin.

Nevertheless, it must be remembered that costs may vary due to regional and seasonal differences and material and energy vary according to the disposal method chosen. But impacts such as toxicity or some risks cannot be changed, since they belong intrinsically to the product. From this point of view, more emphasis on the influencing factors to PBT should be given, since phenolic resins presented toxicity potential 98% higher than PBT.

Moreover, it must be said that, although in the area demand category, the use of wood represented an impact to phenolic resin, this important biomass resource utilization was considered in the material consumption category.

Based on the main critical factors of the base case, 6 scenarios were analysed. Recovery of material (recycling) and energy (incineration) proved to be better solutions to the landfill of the wastes. By incineration, phenolic resin improved its eco-efficiency in 2%. Nevertheless, a reduction in production loss rate (from 20% to 10%), showed to have even a better effect than incineration, since an improvement of 5% was observed. It is certainly difficult to give a realistic scenario when there are still so many open questions and missing data in the development of new processes, but insights gained by the analysis of these scenarios, can give an anticipatory approach of how to proceed in a next step of the research line. For example, this analysis has highlighted the importance of investigating ways to recover phenolic resins.

In the case of PBT, recycling improved its eco-efficiency by 3% in comparison to landfill.

Moreover, the eco-efficiency analysis also showed that a reduction in PBT production costs would have a very positive effect in PBT's eco-efficiency performance, since an improvement of 11% was noticed. Although the method does not discuss ways to achieve it, it points out key factors to the process that can be used as a management tool for future improvements.

Finally, regarding the methodology used, the case study performed here demonstrated to be a very efficient tool in the evaluation of the life cycle burdens of products or processes from both economical and environmental side since it also served as a decision-making instrument. It was useful not only in the comparison of different materials (i.e. comparison of PBT and phenolic resin) but also in the comparison of different process alternatives for the production of the same product, (i.e. comparison of PBT as business as usual (landfill case) and use of recycled material). As a consequence, it can be said that it enables the analysis of different materials for the production of a specific product, as well as the forecast of the environmental and cost effects by the change of parameters in the same process. For many industries, which are passing through such transformation process, such as the automotive, electric and electronic industries as well as others, the use of this tool can be of particular interest.

7.2. Recommendations

Based on the outcomes of this research, some recommendations can be made.

PBT and Phenolic resins:

- ***Promotion of PBT use*** should be stimulated. Considering its environmental advantages, e.g. low risks, low toxicity and recyclability, an increase in its market could reduce more of its costs and therefore improve its economical performance.
- ***Methods to promote recovery of post-consumer wastes*** should be studied. The absences of laws in area, as well as difficulties in their separation are some of the facts that represent a barrier in this work.

- ***Recycling of phenolic resin wastes*** is possible. However producers in Japan still do not practice it. Ways to implement it and support in this direction should be stimulated.

Eco-efficiency methodology:

- ***Research on the inclusion of the social aspects*** would complete the three pillars – environment, economy, and society – required for sustainable development.
- ***Use of this methodology in the design phase of other products or processes*** is theoretically possible. Nevertheless it must be considered that, in the early design stages, most of the data necessary are not available for a detailed LCA. Studies in this sense have actually been developed. But, the use of this eco-efficiency tool is still a challenge.
- ***Improvement of data quantity and quality*** is other important task. Missing or insufficient data needed for the analysis represent a great barrier to the studies.

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