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ENVIRONMENTAL PERFORMANCE ANALYSIS OF SOLID FREEFORM FABRICATION PROCESSES

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Abstract

This paper presents a method for analyzing the environmental performance of Solid Freeform Fabrication (SFF) processes. In this method, each process is divided into life phases. Environmental effects of every process phase are then analyzed and evaluated based on the Environmental & Resource Management Data. These effects are combined to obtain the environmental performance of the process. The analysis of the environmental performance of SFF processes considers the characteristics of SFF technology, includes material, energy consumption, processes wastes, and disposal. Case studies for three typical SFF processes: Stereolithography (SL), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) are presented to illustrate this method.

I. Introduction

Generally, industry ecology involves both processes and products.[1] The interaction of process design with the environment concerns is somewhat different from that of product design. The industry-environment interaction is thus heavily influenced by two rather separate groups of designers. On the side of product design, much of research effort has been taken to develop the concepts, methodologies and implementations of product lifecycle, end of lifecycle factors, and even multi-lifecycle issues. However, processes are much more universal than products, and a successful process design often has great importance to and great staying power for an entire industry. More recently, focuses on studying process level environmental performance have been developed, particularly for conventional machining processes.[2-4]

Solid Freeform Fabrication (SFF), or often referred to as rapid prototyping, provides the physical model of a CAD design using an additive process which builds the physical part layer by layer. This new manufacturing technology has been experiencing tremendous development and growth since its introduction about a decade ago. By the end of 1998, more than 3,000 commercial units were sold and installed worldwide.[9] As a prototype and visualization tool, SFF enables the manufacturer to reduce the overall cost and time to market in the introduction of a new product. Further more, in the application of rapid tooling, SFF can provide masters or patterns to produce molds and dies, or even functional parts. SFF has been widely adopted in aerospace and automotive industries, and has spread to other industries such as medical devices and electronics products. For instance, ceramic materials have been used in many electronics products due to their special properties such as hardness, heat resistance and chemical resistance. The piezo-electricity and superconductivity of some ceramics are also been used to produce special electronic devices. A major problem, however, is that ceramics are brittle and difficult to machine. Solid freeform fabrication of ceramic parts is now becoming an important production process in electronics industry. Certain recycled materials can also be used as feedstock in some SFF processes. For example, the use of recovered CRT glass in photonic bandgap structures is now being explored in Ceramics Research Center of Rutgers University.

In view of the fast growth and wide adoption of various SFF technologies, the environmental performance of SFF processes should be studied, together with other technical specifications, such as accuracy, productivity, and functionality, so that SFF technologies can become more sustainable and environmental friendly. In general, SFF processes have some good environmental characteristics. The waste streams are much less in SFF processes than in conventional manufacturing processes such as machining or molding. Worn tools and scraps seldom occur in SFF. Cutting fluids, which are the major

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source of hazard in the manufacturing waste stream,[2, 5] are not required in SFF processes. However, comparing with conventional manufacturing processes, SFF processes have their distinguishing features in terms of materials, functionality, quality, system complexity, operating style, and so on. It is still necessary to look into the essence of these processes, apply a systematical method to evaluate their environmental property, and derive quantitative assessment of environmental performance for different SFF processes.

This paper presents a hierarchical process model based on life cycle methodology, provides an evaluation method to assess the environmental performance of SFF processes. Three case studies are presented to show the analysis of environmental performance for Stereolithography (SL), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM). Most of the data used in the evaluation is based on the Environment and Resource Management Data from the eco-indicators developed by PRé Consultants of Netherlands.

II. Environmental Aspects of SFF Processes

It has never been a simple task to evaluate and compare different manufacturing processes. Not only it is necessary to weigh the accuracy of processes, the durability of materials, and the energy consumption, but it is also important to measure the productivity, the speed, and the cost of the processes. Our current study is, however, focused only on the environmental issues of SFF processes.

A part produced with a SFF process usually goes through the following stages: (a) loading the building material into the system, (b) building the part layer by layer, and (c) post-processing. Once customers finished the use of the prototyping part fabricated by SFF, it finishes its service time, and it will go to the disposal stage, either to be landfilled or recycled. While preparation of the building material, usage and disposal are not exactly parts of a process, their inclusion provides a holistic view of the environmental performance of the process. Thus, the factors need to be taken into account in terms of environmental performance of processes should include material extraction, energy consumption, processes wastes, and disposal. Table 1 shows the comparison of traditional machining processes with three typical SFF processes: SL, SLS, and FDM in terms of these factors.

Table 1: Comparison of Traditional Machining with SFF Processes

	Material	Energy	Operation	Solid Residues	liquid residues	Aerosol residues	Disposal
Machining	Steel, Aluminum, Alloy	Mechanical energy	Machining, tools needed, multi-steps	Tool scrap, Chip	Fluid mix (cutting, cooling)	Tool particulate, fluid vapor	Landfill, recycling
SL	Liquid photo-polymer	UV laser beam	No tools, building step, post-curing	Small amount of resin cling to the part, removed supports	No	No	Incineration, landfill
SLS	Nylon, poly-carbonate, elastomer, polymer	High power laser beam	No tools, building step, infiltration	Material chips	No	No	Incineration, landfill, recycling
FDM	Nylon, ABS, Investment casting wax, Ceramic	Heat	No tools, one step	Material chips, removed supports	No	No	Incineration, landfill, recycling

III. Process Model and Evaluation Method

A. SFF Process Model

Establishment of a meaningful process model is the core in evaluation of the environmental performance of a process. This model should link the process mechanics with the environmental concerns in each of the process steps, and evaluate their environmental impact values to derive the overall environmental performance of the process. The process model we proposed here is based on lifecycle concept, which has become the backbone in the new industry culture of sustainable production.[6] In the last few years many researchers have been engaged in research and development of lifecycle concept, assessment methods and tools for product designs[6, 7]. The lifecycle concept basically implies that industrial products should be planned and developed for all of their lifecycle phases. Process steps in a SFF process can be viewed as lifecycle phases. Therefore we can build up a total environmental cost model of each SFF process based on the environmental impact values in all process stages.

Based on the lifecycle methodology, we define a general process model with three hierarchical layers as shown in Fig. 1. The top one is the overall environmental performance value, the middle one is the life phases identification, and the bottom one is the environmental impact vector corresponding to each life phase. This model can be used to evaluate the environmental performance of a process once we define its lifecycle phases, identify the individual environmental impact factors, and obtain the environmental impact values.

Five lifecycle phases are defined for SFF processes. They are material preparation, build, post-process, use, and disposal. For each life phase, the Environmental Impact Vector $EIV = [e_1, e_2, \ldots, e_n]$, among which each element represents one kind of environmental impact occurring in this life phase. Eight elements are identified for the *EIV*: Material Extraction (*ME*), Material Production (*MP*), Energy Consumption (*EC*), Residue (*RS*), Material Toxicity (*MT*), Landfill (*LF*), Waste Processing (*WP*), Recycling (*RC*). Not all the eight elements are environmental concerns in every life phase.

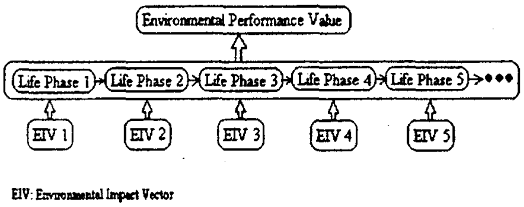

Fig. 1. Process Model for Environmental Performance.

Table 2 shows the distribution of the environmental impact elements in each of the life phases.

Table 2. SFF Process Model Description

Life phase	Name	Environmental Impact Vector
1	Material preparation	*EIV1=[ME, MP]*
2	Build	*EIV2=[EC, RS]*
3	Post-process	*EIV3=[RS]*
4	Use	*EIV4=[MT]*
5	Disposal	*EIV5=[LF, WP, RC]*

B. Environmental & Resource Management Data

In order to use the life cycle based process model to obtain the final environmental performance value, we need unambiguous measures for environmental impact of certain material, basic process, energy, etc. Environmental and Resource Management Data (ERMD) defines what the environment actually is and how to quantify the consequences of impairment of the environment. This data involves not only scientific understanding and measurement, but also social, political and economical issues.

ERMD should be the result of cooperation among industrial experts, environmental scientist, and government legislators. Until recently, there is no complete and practical ERMD database available. In our study, we used the ERMD data, Eco-indicator, collected and calculated by PRé Consultants of Netherlands. The released database contains 100 indicators for commonly used materials and processes. The higher the indicator, the greater the environmental impact. The eco-indicator for a certain material can be obtained as follows. First inventory of all environmental effects and damage are made. Then the normalization is applied to obtain some equivalent effects. Finally weighting factors are used to scale the effects to a certain measure of seriousness. Setting equivalents and weighting factors are subjective choices that are based on more than pure scientific calculation. The principle of Eco-indicators is illustrated in Fig. 2.

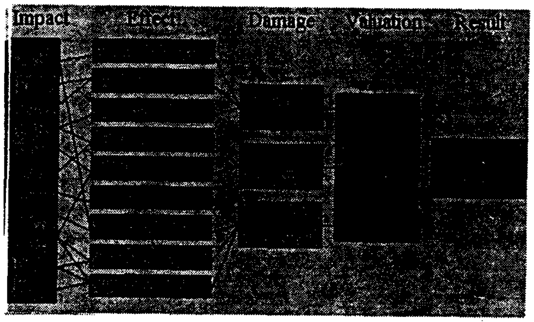

Fig. 2 Principle of Eco-indicator [8]

C. Evaluation Method

To evaluate environmental performance of SFF processes, we have built a process model that deals with the process complexity by dividing a process into life phases. The ERMD data, Eco-indicator, is then employed to provide quantitative measures for each phase of the process. The implementation of this evaluation method can be carried out in the following steps. First, the inventory needs to be done based on the process model. That is, every process phase and the elements of its associated *EIV* vector must be identified and filled in. Then, eco-indicator for each *EIV* element is obtained by looking up the ERMD database. Finally, the environmental indicators for all process phases are summed up to produce the total environmental performance value. This evaluation procedure is illustrated with case studies discussed in the following section.

IV. Case Study

Based on the process model and the evaluation method we presented above, the environmental performance of three widely used SFF processes, Stereolithography (SL), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM), is now analyzed as follows.

Based on the following processing parameters:

V: Scanning (drawing) speed (mm/sec)
W: Road width size (mm)
T: Layer thickness (mm)
ρ: Material density (kg/mm3)
P: Power rate (kW)
k: Process overhead coefficient (0.6~0.9)

the Process Productivity (PP) and the Energy Consumption Rate (ECR) for SL, SLS and FDM can be determined, according to the principle of layered fabrication, as

$$PP\,(kg/h) = V \times W \times T \times \rho \times 3600 \times k$$

and

$$ECR\,(kWh/kg) = \text{Power rate} / \text{Process Productivity}$$

A. Analysis of SL Process

The building material in SL is laser-curing liquid photopolymetric resin. The velocity necessary for a laser to cure a liquid polymer to a specified cure depth, along a single cure line can be calculated by following equation.

$$V=\sqrt{\frac{2}{\pi}}\left[\frac{P_L}{W_0 E_c}\right]\exp\left(-\frac{C_d^s}{D_p}\right)$$ [5]

where P_L is the laser power, E_c denotes the critical laser exposure for the liquid, C_d^s is the specific depth, and W_0 is the laser beam width, and the D_p is the material constant.

We analyze the process based on 3 kinds of equipment, SLA-250, SLA-3000, and SLA-5000. Table 4 shows the result of total energy indicator (product of Eco-indicator for Energy and Energy Consumption Rate) which represent the environmental impact of the energy used to process one kilogram of epoxy resin. Table 5 shows the environmental indicators [8] of the *EIV* elements and the total. Since there are usually two alternatives of disposal, two values are given. The value before "/" is for disposal using landfill and the one after "/" is for disposal using incineration.

Table 4. Energy Indicator of SL Process

	SLA250	SLA3000	SLA5000
V (mm/sec)	340	1000	2000
W (mm)	0.25	0.25	0.25
T (mm)	0.15	0.1	0.1
Specific gravity	1.15	1.15	1.15
k	0.7	0.7	0.7
P (kW)	1.2	3	3
PP (kg/h)	0.0369	0.0725	0.1449
ECR (kWh/kg)	32.47	41.38	20.70
Eco-indicator (/kWh)[8]	0.57	0.57	0.57
Total energy indicator	18.51	23.58	11.79

Table 5. Environmental Performance Analysis of SL Process

Process SL	**Project** Environmental effect for 1Kg material processed		
Equipment SLA 250, SLA 3500, SLA 5000	**ERMD** Eco-indicator[8]		
	SLA-250	**SLA-3500**	**SLA-5000**
Material preparation			
SLA 5170 Epoxy resin	10	10	10
Build process			
Energy in process	18.51	23.58	11.79
Process residues	negligible	negligible	negligible
Use			
Material toxicity	1.2	1.2	1.2
Disposal			
Landfill	0.035	0.035	0.035
Incineration	1.8	1.8	1.8
Total	29.75/31.51	34.82/36.58	23.03/24.79

B. Analysis of SLS Process

The typical building materials used in SLS process include polymer, nylon, polyamide, and polycabonate. Their properties are shown in table 6.

Table 6. SLS Material Property

	Specific Gravity	Eco-indicator[8]
Polymer	1.08	8.4
Nylon	1.04	13
Polyamide	0.97	13
Polycabonate	1.02	13

In this case study, we look into the processes based on two kinds of equipment, Sinterstation 2000 and Sinterstation 2500. Table 7 indicates the energy consumption rate of this process. All the data shown in the table are based on polymer. The values of drawing speed come from the equipment specification provided by DTM Corporation.

Table 7. Energy Consumption Rate of SLS Process

	Model 2000	Model 2500
V (mm/sec)	3000	3000
W (mm)	0.4	0.4
T (mm)	0.15	0.15
Specific gravity	1.08	1.08
k	0.6	0.6
P (kW)	16.8	12.5
PP (kg/h)	0.419	0.419
ECR (kWh/kg)	40.09	29.83
Eco-indicator (/kWh)	0.57	0.57
Total indicator	22.85	17.00

Table 8 is the analysis result of SLS process. Since there are three alternative disposal methods, three values are listed for total in the order of recycling, landfill and incineration.

Table 8. Environmental Performance of SLS Process

Process SLS	**Project** Environmental effect for 1Kg material processed	
Equipment Model 2000, Model 2500	**ERMD** Eco-indicator[8]	
	Model 2000	**Model 2500**
Material preparation		
Polymer	8.4	8.4
Build process		
Energy in process	22.85	17.00
Process residues	negligible	negligible
Use		
Material toxicity	0	0
Disposal		
Recycling	-1.6	-1.6
Landfill	0.077	0.077
Incineration	6.0	6.0
Total	29.65/31.33/37.25	23.80/25.48/31.40

C. Analysis of FDM Process

FDM process forms three dimension objects by extruding thermoplastic material from a temperature controlled head and depositing the material in ultra-thin layers. The typical material processed by FDM is ABS. In this case study, we investigate processes based on machine models FDM1650, FDM2000, FDM8000, and FDM Quantum. The energy consumption rate of FDM process is shown in table 9. Table 10 demonstrates the analysis result of FDM process. Three values for total are in the order of recycling, landfill and incineration.

Table 9. Energy Consumption Rate of FDM Process

	FDM 1650	FDM 2000	FDM 8000	FDM Quantum
V (mm/sec)	2	10	50	200
W (mm)	1.4	1.4	1.4	0.4
T (mm)	0.4	0.4	0.4	0.2
Specific gravity	1.05	1.05	1.05	1.05
k	0.9	0.9	0.9	0.9
P (kW)	1.32	2.2	2.2	11
Process Productivity (kg/h)	0.00381	0.0191	0.0953	0.0672
Energy Consumed Rate (kWh/kg)	346.4	115.2	23.08	163.69
Eco-indicator for Energy (per kWh)[8]	0.57	0.57	0.57	0.57
Total indicator	197.45	65.66	13.15	93.30

Table 10. Environmental Performance of FDM Process

Process FDM	**Project** Environmental effect for 1Kg material processed			
Equipment FDM1650, FDM2000, FDM8000, FDM Quantum	**ERMD** Eco-indicator[8]			
	FDM1650	**FDM2000**	**FDM8000**	**FDM Quantum**
Material preparation				
ABS	9.3	9.3	9.3	9.3
Build process				
Energy in process	197.45	65.66	13.15	93.30
Process residues	negligible	negligible	negligible	negligible
Use				
Material toxicity	0	0	0	0
Disposal				
Recycling	-9.5	-9.5	-9.5	-9.5
Landfill	0.035	0.035	0.035	0.035
Incineration	1.8	1.8	1.8	1.8
Total	197.25/206.79 /208.55	65.46/75.00 /76.76	12.95/22.49 /24.25	93.1/102.64 /104.4

V. Conclusion

A life-cycle based evaluation model for analyzing environmental performance of SFF processes is presented. For assessing a process in terms of its environmental performance, material, energy, and disposal scenarios are important issues. The evaluation model is applied to analyze the environmental performance of three SFF processes, SL, SLS, and FDM. For each process, the results are varied for different combination of building material, process equipment, and disposal scenarios. The results of this study only represent the aspect of environmental effects for SFF processes. To assess the whole value of any SFF process, other technical issues [10, 13], such as accuracy, capacity, cost, efficiency, etc., should all be considered.

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