ASSESSMENT OF ENVIRONMENTAL PERFORMANCE OF RAPID PROTOTYPING AND RAPID TOOLING PROCESSES

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Abstract: A method for assessing the environmental performance of solid freeform fabrication (SFF) based rapid prototyping and rapid tooling processes is presented in this paper. In this method of assessment, each process is divided into a number of life stages. The environmental effect of each process stage is analyzed and evaluated based on an environmental index utilizing the Eco-indicators that were compiled by PreConsultants of the Netherlands. The effects of various life stages are then combined to obtain the environmental performance of a process. In the assessment of SFF processes, we consider the material use in the fabrication of a part, energy consumption, process wastes, and disposal of a part after its normal life. An example is given to illustrate this assessment method applied to the stereolithography (SLA) process and two SLA based rapid tooling processes.

Keywords: Solid Freeform Fabrication, Rapid Prototyping, Rapid Tooling, Environmental Performance, Lifecycle Analysis.

1 INTRODUCTION

Industrial ecology involves both manufacturing processes and products. The interaction of process design with environmental concerns is somewhat different from that of product design. The industry-environment interaction is thus 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 implementation of product lifecycle, end of lifecycle factors, and even multi-lifecycle issues [1-3]. However, processes are more universal than products, and a successful process design often has great importance to an entire industry. More recently, focused studies on process-level environmental performance have been developed, particularly for conventional machining processes [5-7].

Solid Freeform Fabrication (SFF), or often referred to as Rapid Prototyping (RP), produces the physical model of a CAD design using an additive process that builds the physical part layer by layer. This new manufacturing technology has been experiencing tremendous development and growth since its introduction a little over one decade ago. By the end of 1998, more than 3,000 commercial units of SFF machines were sold and installed worldwide [9]. As a prototyping and visualization tool, SFF enables the manufacturer to reduce the overall cost and time to market in the introduction of a new product. Furthermore, in the application of Rapid Tooling (RT), SFF

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technique allows direct or indirect manufacture of production tools, which has created a competitive edge [12]. SFF has been widely adopted in aerospace and automotive industries, and is quickly spreading to other industries that manufacture medical devices, electronics products, etc.

In view of the fast growth and wide adoption of various SFF processes, it is important to study the lifecycle performance of SFF processes, including consumption of natural resources and energy, and impact on human health and the environment, together with other process attributes such as cost, accuracy, productivity, and functionality, so that the SFF technology can become more sustainable. SFF processes have some good environmental characteristics. The waste streams are less in SFF processes than in conventional manufacturing processes such as machining. Worn tools and scraps seldom occur in SFF processes and equipment. Cutting fluids, which are the major source of hazard in machining [5-7], are not used in SFF processes. Comparing with conventional manufacturing processes, SFF processes have distinguishing features in process mechanisms, materials, energy use, etc. It is essential to look into these processes, investigating how the process variables influence the environmental consequences, and apply a systematic method to assess the process environmental performance so that these processes can be optimized with consideration of their environmental properties.

In [14], we reported some preliminary results of our research towards a systematic approach that we developed for SFF processes based on lifecycle concept. A lifecycle process model was proposed, in which a process' entire lifecycle is considered and it is divided into several life stages. Environmental impact is evaluated for each life stage and then combined to obtain the overall environmental performance for a process. This method has been used to assess Stereolithography (SL), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) processes. Besides the environmental performance, process cost, process quality, and other factors can be incorporated to develop a multi-objective decision making method. The approach was introduced in [15].

In this paper, we extend the previous method to assess SFF based rapid tooling processes. As for the SFF processes, the method holistically incorporates the entire process lifecycle, including material extraction, pattern fabrication, shape replication, post processing, and material disposal. The environmental performance is evaluated, based on Lifecycle Assessment (LCA) principle [1-3] and with an environmental impact index called the Eco-indicator [8]. Details of this method and an example illustrating its use will be given.

2 LIFECYCLE ENVIRONMENTAL PERFORMANCE OF RAPID PROTOTYPING AND RAPID TOOLING PROCESSES

LCA has been found useful for examining the design of products and processes to reduce the impact upon human health and the environment and to achieve sustainable industrial development. From the lifecycle point of view, a part produced with a SFF process generally goes through the following stages: (a) inputting the building material into the system, (b) building the part layer by layer, (c) shape replication and sintering or burning (for tooling processes) and (d) post-processing. When the user finishes using the part fabricated by SFF, the part goes to the disposal stage: to be landfilled, incinerated, or recycled. While the material, part usage and part disposal are not exactly part of a process, their inclusion provides a holistic view of the environmental performance of an SFF process. Thus, factors taken into account in process environmental performance should include the material extraction stage, energy consumption and process wastes in the fabrication and replication stages, and the disposal stage. In terms of these environmental factors, we first provide a general comparison between conventional machining process and several SFF processes, as given in Table 1.

Table 1. Comparison of Machining with SFF Processes

	Materials	*Material Utilization*	*Energy Source*	*Process Residues*	*Disposal*
Machining	*metals, alloys, ceramics, etc.*	*material-removal process. Material Utilization Rate (MUR) is 60% - 90%*	*electromotor power (mechanical energy)*	*material chips, tool scraps &chips, cutting fluids, fluid vapor*	*landfill, recycling*
SLA	*liquid photo-polymers etc.*	*material-additive process. MUR almost 100%*	*UV laser (chemical energy)*	*material chips, removed support structures*	*incineration, landfill*
SLS	*powder of nylon, plastics, metals, ceramics, etc.*	*material-additive process. MUR about 100%*	*high power laser (thermal energy)*	*material chips*	*incineration, landfill, recycling*
FDM	*nylon, ABS, wax, ceramics, etc.*	*material-additive process. MUR almost 100%*	*heat (thermal energy)*	*material chips, removed support structures*	*incineration, landfill, recycling*

To evaluate the environmental performance, we propose a process model based on lifecycle concept. The steps of an SFF process can be viewed as the process lifecycle stages, and thus the environmental impact factors in all process stages can be included in this model. The model is then extended for assessment of SFF based Rapid Tooling (RT) processes.

The environmental performance process model is shown in Figure 1. Figure 2 is an extension of this model for RT processes. In the process model, the overall environmental performance value is the sum of the environmental performance values of the various life stages, each of which has one or more corresponding environmental impacts. The environmental performance of a process is evaluated by defining the lifecycle stages of the process, identifying the individual environmental impact factors, obtaining the environmental impact values, and summing these values.

Figure 1 shows that the lifecycle of a process can be divided into n stages. For SFF process, there are generally four lifecycle stages: 1) material preparation, 2) part build, 3) part use, and 4) part disposal. Environmental impacts that occur in each lifecycle stage are identified as follows. In the material preparation stage, the environmental impact is material extraction & production. During the part building stage, the main environmental impact is energy consumption. Process residues, such as cutting fluids, which exist and have severe environmental consequences in the part cutting stage of machining process, are rare in most of SFF processes, and can be ignored in evaluation. Material toxicity may cause negative impact to human health in the part use stage. Finally in the disposal stage, the part can be landfilled, incinerated or recycled. Different disposal methods have different environmental impacts.

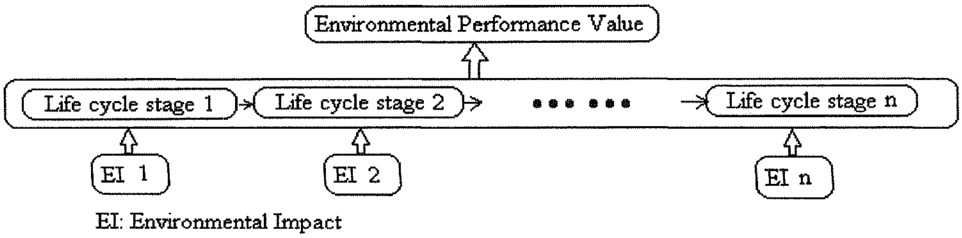

Figure 1. Lifecycle environmental performance model

The model presented above is the basic process model for SFF processes. It can be extended to SFF based RT processes. Here we consider indirect RT processes, in these processes, a few additional steps are needed to duplicate the shape of the pattern made by SFF, and then sintering or burning the duplicate part is needed to get the tool. These steps are needed for the mold creation, and they can be seen in, for example, 3D Keltool and the rapid tooling process that integrates SFF with electroforming. The extended process model for indirect RT processes is shown in Figure 2. The environmental impacts corresponding to every lifecycle stage need to be identified. In the figure 2, EI1 is for material extraction & production. EI2 is for energy consumption. EI3 includes material consumption, energy consumption and process residue. And EI4 results from the tool disposal stage where the tool can be landfilled, incinerated or recycled.

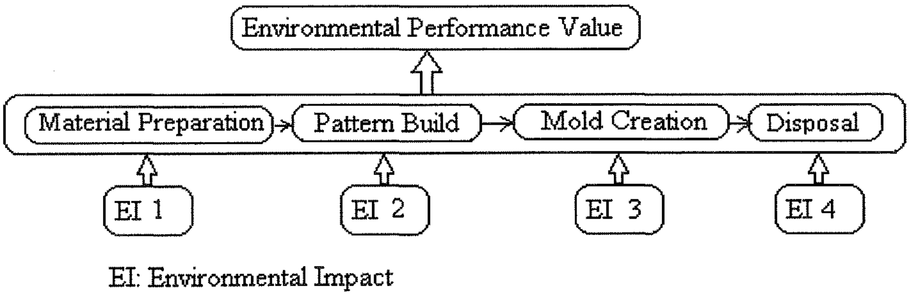

Figure 2. Lifecycle environmental performance model of indirect RT process

The environmental performance value obtained should provide an unambiguous measure for the combined environmental impact of material, process, energy, etc. This kind of data quantifies the impact of the process to the environment. It should be noted that there is no database of this kind available today. For performing the quantitative assessment, we use the Eco-indicator index [8] that was made available by PréConsultants of the Netherlands. The provided database contains 100 indicators for commonly used materials and processes. The higher the indicator, the greater the negative environmental impact.

To summarize, our process model deals with the process complexity by dividing a process into several life stages. The environmental impact index provides a quantitative measure of environmental impact for each stage of the process. The implementation of this evaluation method can be carried out as follows. First, every process stage and the elements of its associated environmental impact factors are identified. Then, the value of eco-indicator is obtained for each environmental impact factor. Finally, the environmental index values for all process stages are summed up to generate the total environmental performance value.

3 EXAMPLE: ASSESSMENT OF SLA PROCESS AND SLA BASED RAPID TOOLING PROCESS

This example considers the StereoLithography (SLA) process and two rapid tooling processes that utilize SLA to build patterns: 3D System's Keltool process [14] and an SFF based electroforming process [13]. SLA is one of the most widely used SFF processes today. It is a fabrication process that builds a part by controlling a laser beam to selectively cure liquid photopolymer layer by layer. 3DKeltool and electroforming tooling processes are two rapid tooling processes that utilize SLA to quickly create highly detailed and accurate patterns.

For the SLA process, the process parameters that influence the environmental performance are identified as follows:

M: Material used (cm^3)
V: Scanning speed (mm/sec)
W: Line width (mm)
T: Layer thickness (mm)
P: Power rate of the equipment (kW)
k: Process time delay between layers (coefficient = 0.6~0.9)

The scanning speed can be estimated using the following equation [4]:

$$V = \sqrt{\frac{2}{\pi}}\left[\frac{P_L}{W_0 E_c}\right]\exp\left[-\frac{T}{D}\right] \quad (1)$$

in which P_L is the laser power, W_0 is the half line width, Ec is the critical laser exposure, and D is a material constant of the polymer.

The Process Productivity (PP) and the Energy Consumption Rate (ECR) for each unit volume of material processed can be calculated as follows:

$$\text{PP (cm}^3\text{/h)} = V \times W \times T \times k \times 3600 / 10^3 \quad (2)$$

and

$$\text{ECR (kWh/cm}^3\text{)} = P/\ PP \quad (3)$$

The environmental performance of SLA process is evaluated according to the assessment method introduced in section 2.

3.1 Assessment of SLA Process

The building material in the SLA process is photopolymetric resin. The process is evaluated with three models of the equipment, SLA-250, SLA-3500, and SLA-5000. The manufacturer's recommended process parameter values are used in the assessment. First we need to obtain the environmental impact due to energy consumption in the process. Here we use equation (1) to calculate the process scanning speed *V*, then use equation (2) and (3) to estimate the process energy consumption rate (ECR). Finally we obtain the environmental impact of energy consumption. Table 2 shows the result representing the environmental impact of the energy used to process one cm^3 of epoxy resin. Because SLA-5000 has the highest laser power, resulting in the highest scanning speed, and the least ECR. While for SLA-3500 and SLA-250, the former one has higher scanning speed but also higher power rate of equipment than the later one. The result gives that the SLA-250 has less ECR than SLA-3500.

Table 3 shows the environmental indicators of the environmental impact occurring in each lifecycle stage of the process, and the environmental performance value representing the total environmental impact. As we discussed in section 2, the environmental impacts in various lifecycle stage are identified and the corresponding index values are obtained from the Eco-indicator database, and converted to the values representing effect of one cm^3 of specific material. Since there are usually two alternatives of disposal, two values are given for the disposal stage. The value before "/" is for disposal using landfill and the one after "/" is for disposal using incineration.

Table 2. Environmental Impact Due to Energy Use of SLA Process

	SLA-250	*SLA-3500*	*SLA-5000*
V (mm/sec)	*340*	*1000*	*2000*
W (mm)	*0.25*	*0.25*	*0.25*
T (mm)	*0.15*	*0.1*	*0.1*
k	*0.7*	*0.7*	*0.7*
P (kW)	*1.2*	*3*	*3*
PP (cm^3/h)	*32.13*	*63.00*	*126.00*
ECR (kWh/cm^3)	*0.037*	*0.048*	*0.024*
Eco-indicator (/kWh) [8]	*0.57*	*0.57*	*0.57*
Environmental Impact	*0.021*	*0.027*	*0.014*

Environmental Impact = ECR × Eco-indicator

Table 3. Environmental Impact of SLA Process

Process *SLA*	***Project*** *Environmental effect for 1* cm^3 *material processed*		
Equipment *SLA-250, SLA-3500, SLA-5000*	***Environmental impact index*** *Eco-indicator*		
	SLA-250	***SLA-3500***	***SLA-5000***
Material preparation			
SLA 5170 Epoxy resin	*0.012*	*0.012*	*0.012*
Part build			
Energy use	*0.021*	*0.027*	*0.014*
Disposal			
Landfill/Incineration	*4.03e-5/0.0021*	*4.03e-5/0.0021*	*4.03e-5/0.0021*
Total Impact	*0.033/0.036*	*0.039/0.042*	*0.026/0.029*

3.2 Assessment of Two Rapid Tooling Processes

3D KelTool and the SFF based electroforming process are two indirect rapid tooling processes. Indirect tooling requires a master pattern built by SFF process. At least one intermediate step is needed. The intermediate steps may include shape replication and sintering or burning in the manufacture of the production tool.

3D Keltool process [14] can be used to rapidly create injection molds or die casting inserts. It begins with an SLA master pattern. The pattern is used to produce an RTV silicone rubber mold. Once the RTV mold is produced, it is then filled with a mix of tooling steel powder, tungsten carbide powder and epoxy binder. After this material has cured in the mold, this "green part" is sintered in a hydrogen-reduction furnace and the binder material is burning off. The final step is to infiltrate the sintered part with copper.

The SFF based electroforming process [13] can be used to produce EDM electrodes, molds and dies. First, an SLA pattern is fabricated. Then the pattern is metalized and electroformed in nickel or copper solution. When the desired thickness of metal shell is reached, the SLA pattern is removed by burning out. Finally, the metal shell is backed with other materials to form the production tool.

Figure 3 illustrates the concepts of these two indirect tooling processes. When a cylindrical metal mold cavity is required to be manufactured, both 3D Keltool and SFF & Electroforming processes have this function, although they differ from each other in type and amount of materials use and specific intermediate steps. If we are going to look into the environmental performance, the model introduced in section 2 can be used to assess them from the lifecycle viewpoint.

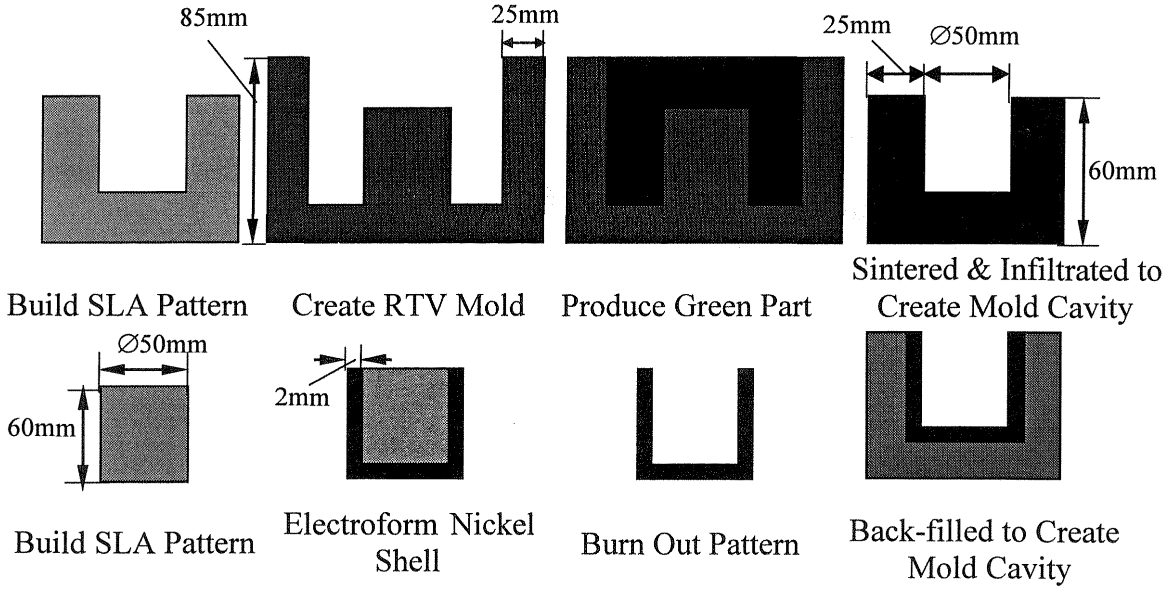

Figure 3. Indirect Tooling Process

Unlike the assessment of SFF process in which only unit volume of material is considered, In evaluating indirect RT processes, the volume of final tool should be accounted in order to estimate the amount of intermediate material consumed. In the following assessment, the cylindrical mold cavity in figure 3 is used as an example with dimensions of diameter 50mm and height 60mm.

In the pattern building stage, we can use the assessment result for the SLA process and assume the two RT processes both use SLA 250 to fabricate the master pattern. The environmental impact for unit volume (cm^3) SLA material consumed is 0.034. Since 3D Keltool uses the negative pattern and SFF & Electroforming uses positive pattern, different volume of materials used yield different impact values for this stage. Here we assume the dimensions of the mold is 100mm diameter and 90mm height. The material volumes of 3D Keltool process used to build the pattern is $589.4cm^3$ and that of SFF & Electroforming process used is $117.2cm^3$.

In the mold creation stage, material consumption, process residues and energy consumption during sintering or burning step should all be considered. In this stage, 3D Keltool typically consumes silicone and mixed steel powder, The environmental indices for unit volume (cm^3) of silicone and mixed steel are 0.036 and 0.156 respectively. And the volumes of RTV mold and the final mold also need too be calculated. Therefore the material consumption impact in this stage can then be estimated. Similarly, SFF & Electroforming process usually use nickel to electroplate certain thickness of metal shell, and then back filled with aluminum. For unit volume (cm^3) of nickel and aluminum, the environmental indices are 0.534 and 0.049 respectively. The nickel shell thickness is typically 2mm. So the volume of nickel and aluminum used can be calculated. And hence we can get the material consumption impact in this stage for SFF & Electroforming process. The results can be seen in the table 4. Sintering and burning in 3D Keltool and the electroforming tooling process require to consume energy. The energy consumption is estimated as production of furnace power rate and sintering or burning time. The electroforming tooling process needs more energy than 3D Keltool in this stage because burning off the SLA pattern consumes more energy.

In the disposal stage, The 3D Keltool process produces wastes such as SLA material and silicone. Electroforming tooling process only has residue of SLA material. If the process residue are all disposed to landfill, the environmental impact can be assessed by considering the impact indices and the volume disposed. The results are shown in table 4. In addition, we expect the disposed tools can be recycled by material recovering. The mixed metal of the tool made by 3D Keltool is less preferable than laminated nickel and aluminum used in the electroforming tooling process. The impact indices for recycling unit volume (cm^3) of mixed steel, nickel, and aluminum are -0.023, -0.311, and -0.035 respectively.

Table 4 shows the assessment results for the above two indirect RT processes.

Table 4. Environmental Performance of RT Process

Process *3D KelTool* *SFF based Electroforming Tooling*	***Project*** *Environmental effect for RT processes*	
Base SFF process *SLA*	***Environmental impact index*** *Eco-indicator*	
	3D KelTool	*SFF & Electroforming*
Pattern build		
Material use	*7.07 (SLA material)*	*1.41 (SLA material)*
Energy use	*12.38 (energy used in pattern building)*	*2.46 (energy used in pattern building)*
Mold creation		
Material use	*80.97 (silicon and mixed steel powder)*	*40.61 (nickel and aluminum)*
Energy use	*0.25 (energy used by furnace)*	*0.57(energy used by furnace)*
Disposal		
Process residues landfill	*0.088 (SLA material and silicon)*	*0.033 (SLA material)*
Material recovery	*-13.56 (mixed steel)*	*-26.67 (nickel and aluminum)*
Total impact	*87.76*	*18.52*

From the above assessment, we can see that the environmental performance of a rapid tooling process depends on several factors. First, the selection of the base SFF process is an important factor. It is desirable to select an SFF process that has good environmental performance Secondly, the tooling materials, and process residues can further impact on the environmental performance due to the use of natural resources and possible generation of process residues. Finally, the method of disposal or recovery of tool material will also influence the total environmental performance of a process.

4 CONCLUSION

A lifecycle based process model for analyzing environmental performance of SFF processes and SFF based rapid tooling processes is extended for analyzing SFF based RT processes. The process environmental performance assessment model considers material, energy, and disposal scenarios. The material use, process parameters (e.g. scanning speed) and power use can affect the environmental consequence of a process when material resource, energy, human health and environmental damage are taken into account. The presented method is applied to the SLA process and two SLA based rapid tooling processes. The method can be used to compare different RP and RT processes in terms of their environmental friendliness.

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