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EVALUATION AND RE-DESIGN METHOD OF MANUFACTURING PROCESSES

S. Kondoh, N. Mishima, Y. Hotta, K. Watari, T. Kurita and K. Masui

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1. Introduction

To achieve sustainable society, it is important to reduce environmental impact of manufacturing processes. However, for manufacturing engineers, enhancing manufacturing quality has long been the most significant goal. Therefore, in order to encourage development of environmentally conscious manufacturing technologies, it is necessary to evaluate manufacturing quality. One answer is the "eco-efficiency [Tahara, 2004]." Eco-efficiency is a useful index for evaluating environmental and economical aspects simultaneously. However, the eco-efficiency cannot evaluate each component of the product, or each segment process of the total manufacturing process. It is difficult to suggest design improvement strategies using eco-efficiency. We propose a new product efficiency indicator named "total performance indicator [Kondoh, 2006] (TPI)." TPI can be a powerful tool in determining design strategies for "green products." In this paper, we try to apply TPI to manufacturing processes. By calculating TPI of each segment process, bottleneck segment processes in enhancing quality of manufacturing can be clarified. This paper takes ceramic diesel particulate filter (DPF) as an example and allocates quality characteristics to functional requirements of the product. Then, it quantifies the contribution of each segment process in creating the product value. A segment process which doesn't contribute much to create value and generates considerable environmental impact and cost should be improved. By taking these steps, it is expected that a designer can determine which products and processes are really environmentally benign.

2. Proposal of process TPA (Total Performance Analysis)

2.1 Basics of TPA

In present research, we propose an index to evaluate real performance of products, by considering product's utility value, cost and environmental impact, throughout the product lifecycle. Efficiency indicator is defined by (1) and is named total performance indicator (TPI).

$$TPI = \frac{UV}{\sqrt{LCC}\sqrt{LCE}} \tag{1}$$

TPI: Total performance indicator, *UV*: Utility value of the product
LCC: Life-cycle cost of the product
LCE: Life-cycle environmental impact of the product

Eco-efficiency is one of common indexes in design for environment [Ernzer, 2003]. However, existing evaluation indexes cannot evaluate environmental and economical aspects simultaneously. In addition, since the “value” in the eco-efficiency index is usually a fixed value, it cannot consider change of the value throughout the product life cycle. The proposed index is the simplest combination of the environmental and economical efficiencies. In our proposal, because the utility value of the product can be expressed by integration of occasional values throughout the lifecycle, it can simulate value decrease due to obsolescence and physical factor. (Figure 1) In the figure, the value of the product is defined as the area of the region that is surrounded by the value decrease curve of the use stage and the value increase curve of the production stage. By changing the shape of these two curves, it is possible to simulate development lead-time, production lead-time, product life and so on. Our proposing TPI could be an answer to the problems in existing eco-performance indicators.

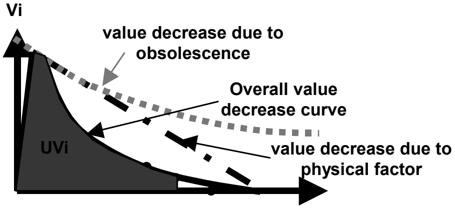

Figure 1. Value decrease throughout product lifecycle

2.2 Extension of TPA to process evaluation

As it was mentioned, it is important to take manufacturing quality into account to persuade manufacturing engineers to become be positive in reducing the environmental impact of manufacturing processes. Because the As design engineers and manufacturers have a long history of making serious efforts to reduce cost of manufacturing costs, they might not accept an indicator that does not evaluate cost and functionality. So, the evaluation method should be able to quantify ‘high quality of manufacturing,’ which is a very qualitative expression. The idea of process TPA is based on product TPA. To evaluate the efficiencies of manufacturing processes, the same idea can be applied. We define the total performance of the manufacturing process by (2). The equation expresses the balance of the product value created by the manufacturing process, versus the cost and environmental impact necessary to fabricate a product.

$$PROCESS\ \ TPI = \frac{UV}{\sqrt{\sum_{i=1}^{i=n} PE_i \cdot \sum_{i=1}^{i=n} PC_i}} \tag{2}$$

PCi: Cost of a segment process, *PEi*: Environmental impact of a segment process
n: Number of processes

The numerator “*UV*” of the equation may change due to manufacturing quality. For example, a product with higher profile accuracy or smoother surface is likely to have a higher value than a similar product that uses a lower level of manufacturing techniques. Or, a machine with hardened surface (by heat treatment etc.) usually has a longer lifetime than a similar machine that does not use heat treatment. As shown in Figure 1, a longer lifetime directly means higher “utility value.” It is evident from these examples that manufacturing quality significantly affects the utility value of the product. At the same time, manufacturing quality also has a strong relationship between cost and environmental impact of the process. For example, in precision machining, it is known that cost and environmental impact may vary due to the cutting conditions [Narita, 2004] and usually they are larger when the manufacturing quality is higher. For these reasons, in evaluating manufacturing processes, it is necessary to consider manufacturing quality versus cost and environmental impact simultaneously.

2.3 Concept of improving the manufacturing process

When evaluating the manufacturing processes as an inseparable set of processes, will the abovementioned equation be sufficiently useful. However, the purpose of the evaluation is to obtain suggestions for process improvement. So, it is necessary to evaluate the TPI of each segment process and to determine any bottleneck segment processes in enhancing the TPI of the total manufacturing process. Figure 2 indicates the concept of improving the TPI by focusing on a bottleneck segment process. The bottleneck segment process is shown as a segment line with a shallow inclination. For example, Segment process 2 in the figure does not contribute much in creating the final product value, but it generates relatively large cost and environmental impact. In such a case, basically, there are 3 ways to improve the TPI of the total process: (1-1) To reduce the environmental impact or cost of the process; (1-2) To enhance the process quality; and (2) Tp apply a new combination of processes. All approaches may enhance process TPI. Of course, this approach does not mention anything about whether the focused segment process is actually improvable, or not. To apply the design evaluation method to an actual process and to ensure improvement, it is indispensable to collaborate with process engineers who are aware of problems in their manufacturing process. They usually have thorough knowledge about the process and the products made by the process. Knowledge about the actual manufacturing process is necessary in order to put this approach into practice.

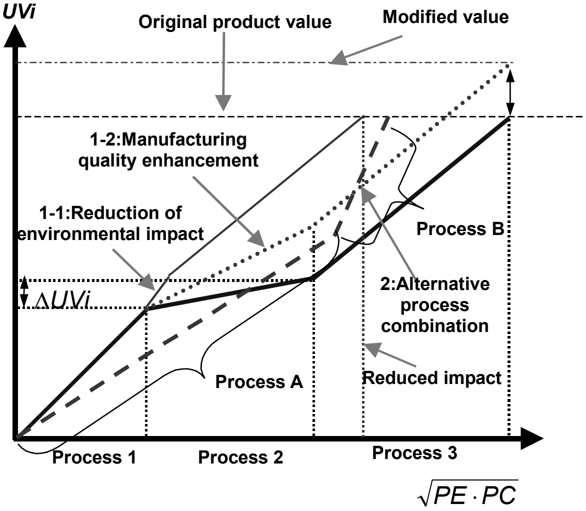

Figure 2. Methods for improving process TPI

3. Example of process TPA

3.1 Definition of target product

To show the actual procedure of process TPA and improvement of a process, a practical example is examined. As the target product, we chose a ceramic diesel particulate filter (DPF), an overview of which is shown in Figure 3. Ceramic DPF is used frequently because of its high thermal endurance and high specific strength. One of the purposes of this paper is to apply TPA to a specific process and quantify the effect of process improvement. Roughly speaking, the main function of a DPF is to eliminate particulate matters generated by diesel combustion. But, the function can be separated into 5 more detailed functional requirements. Then, the 5 functional requirements can be related to 12 quality characteristics. Defined functional requirements and quality characteristics are shown in Table 1 on the next page. The price of the filter unit is assumed to be 20,000 JPY.

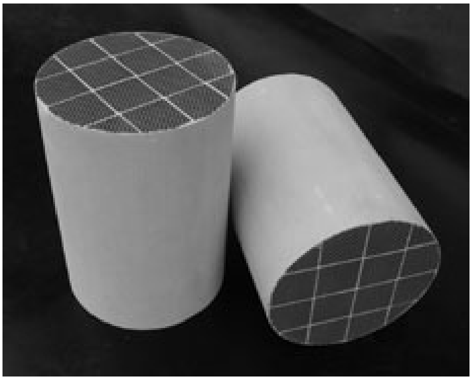

Figure 3. Example of ceramic DPF

3.2 Allocation of product value to functional requirements and quality characteristics

Applying QFD [Akao, 1990], [Kondoh, 2007], it is possible to clarify the importance of each functional requirement of a DPF. We set 5 functional requirements (FR) and 12 quality characteristics to the filter. Table 1 shows how each functional requirement is allocated to the quality characteristics. By considering the importance of each FR, it is possible to determine the value of FRs within the total value of the product (20,000 JPY). The chosen FRs are all important. In other words, we chose important functional requirements only. Therefore, the analysis suggests that the value of each FR occupies 1/5 of the total value of the DPF

Table 1. Relationship between functional requirements and quality characteristics of a ceramic DPF

		Functional requirements					
		Capability of particulate matters	Fuel loss due to pressure loss	Fuel loss due to reproduction	Life	Reliability (crack-free)	Total
Importance of functional requirement		9	9	9	9	9	54
Value of functional requirement (K yen)		4	4	4	4	4	20
Quality characteristics of DPF	Thermal conductivity					9	9
	Coefficient of thermal expansion					9	9
	Thermal endurance		3	3		9	15
	Pore rate	9	9				21
	Specific heat capacity			9			9
	Uniformity of pore distribution	3	3				6
	Average pore diameter	3					3
	Surface activity of the material						0
	Mechanical strength				3		3
	Profile accuracy (length)	9				3	12
	Profile accuracy (section)	9				3	12
	Uniformity of the material composition				9	3	12
	Sum total of the importance of functional requirements	33	15	12	21	36	108

3.3 Allocation of processes to quality characteristics

The second step of the analysis is to determine the contribution of each segment process to the value creation. By identifying the relationship between segment processes of the total manufacturing process and the quality characteristics, it is possible to calculate the value of the segment processes. We dismantled the total manufacturing process into 6 segment processes. Table 2 shows the results of the calculation of process value. As indicated in the table, the values of quality characteristics are calculated first. The results show that some characteristics such as “pore rate,” “specific heat capacity,” etc. occupy a relatively large portion of the value. Therefore, it is assumed that a segment process contributing to achieve these quality characteristics has a high value. The table shows that “mixture of base materials” has the highest value and “ball milling” has the second highest value.

Table 2. Relation between quality characteristics and manufacturing processes

			Segment process						
			Mixture of base materials	Ball milling	Injection molding	Binder removal	Sintering	Bonding of honeycomb unit	Total
Quality characteristics of DPF	Thermal conductivity	1	9	3					12
	Coefficient of thermal expansion	1	9	3					12
	Thermal endurance	2.8		9	3	1	1		14
	Pore rate	3.5	9	3	1	1	1		15
	Specific heat capacity	3	9						9
	Uniformity of pore distribution	1.2	1	3	3	3	1		11
	Average pore diameter	0.4	9	3					12
	Surface activity of the material	0	3	1		1	1		6
	Mechanical strength	1		3	3	3	3	1	13
	Profile accuracy (length)	1.4	9	3				1	13
	Profile accuracy (section)	1.4	9	3				1	13
	Uniformity of the material composition	3.3		3		3	1		7
	Value of the process (K yen)		8.95	5.72	1.38	2.41	1.25	0.29	20
	Yield rate of process		0.99	0.6	0.8	0.95	0.95	0.95	-
	Real value of process (K yen)		8.86	3.43	1.1	2.29	1.18	0.28	17.1
	Environmental impact of process (kg-CO2/unit)		5	1	1	8	9	0.1	
	Cost of process (K yen)		5	3	1	4.5	1	1	

In an actual manufacturing process, the output of a certain process is usually the input of the next process. These intermediate properties often do not affect the quality of the final product, but they do affect the following processes. For example, ball-milled slurry often has high viscosity and causes relatively large shrinkage during “sintering.” Although the viscosity of the slurry does not affect the final product, it strongly affects the quality of “sintering.” It is necessary to consider these interactions between segment processes. To express the interaction, “yield rate” is introduced. In the example process for DPF, “ball milling” has relatively low yield rate. This that there are some uncertainties in this process and some of the intermediate products of “ball milling” do not satisfy the requirements of “sintering.” The low yield rate is reflected in the table as the “real value” of the segment process. Since this manufacturing process is a practical process used in industry, it is possible to measure the environmental impact and cost of each segment process. However, since the purpose of this report is to propose a procedure to evaluate total performance of manufacturing process and obtain suggestions for process improvement, showing the example of improvement is enough. Therefore, values of the cost and environmental impact were roughly estimated. By using the calculated value and estimated environmental impact and cost, the TPI of segment processes can be calculated.

3.4 Analysis of the manufacturing process

Using value, cost and environmental impact, a TPI graph can be drawn. Figure 4 is the TPI graph of the original manufacturing process. The solid line indicates the unadjusted value. The dotted line shows the adjusted value when interactions between segment processes are considered by introducing yield rate. The inclination of a segment line shows the TPI of the corresponding segment process. The inclination of a virtual line connecting the starting-point and the end-point indicates the TPI of the total process. Compared to the TPI of the total process, segment processes "binder removal" and "sintering" have a lower TPI, and the other processes have a relatively higher TPI. This is because "binder removal" and "sintering" require temperature rise of the material using a furnace, which consumes a large amount of energy. In addition, "binder removal" emits hazardous substances due to the organic binder material. The cost of eliminating the substances is roughly considered in the cost of the segment process.

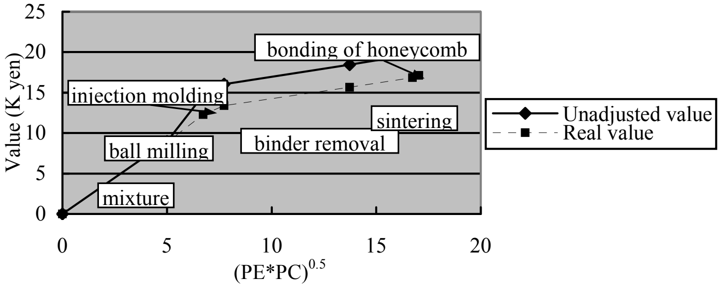

Figure 4. TPI of the manufacturing process of a DPF

4. Evaluation of improved process

4.1 Strategies for process improvement

To improve the TPI of the total process, we should focus on a segment process having a shallow inclination. The strategies for process improvement (re-design) can be categorized as shown in Table 3. Basically, all the segment processes are targets to consider process improvement options. However, there are some limitations in the actual manufacturing process. Firstly, materials to be mixed are strictly determined in order to ensure overall performance of the filter. Secondly, "injection molding" is suggested to be removed. But, currently there is no candidate for an alternative process. Thirdly, "bonding of honeycomb unit" should be also removed, because the value created by the process is very small. However, since the cost and the environmental impact of this segment process are very small, big effect of improvement cannot be expected. Because of these reasons, "ball milling," "binder removal" and "sintering" are identified as the actual process improvement targets.

Table 3. Categorization of low TPI and design options

Expression of segment lines on the TPI viewgraph			Process improvement option
Shallow inclination	Small increase of real value	Small increase of unadjusted value	Consider removal of the specific process
		Low yield rate	Try to enhance the yield rate by identifying critical requirements of the following process
			Change the design range or loosen the tolerance
	Large impact * cost		Try to reduce cost and environmental impact
Large width	Large impact * cost		Try to reduce cost and environmental impact

4.2 Comparison with actual process improvements

Improvement of the DPF manufacturing process is an ongoing research topic. Some methods for enhancing the performance of the process or reducing the process time have already been studied. The purpose of using the DPF production process as an example is to ensure that the design approach does not contradict the process engineer's knowledge, and to show that it is possible to simulate the effect of the improvement. Therefore, it is necessary to analyze actual improvement. New manufacturing processes have been proposed for significant enhancement of manufacturing speed and productivity of ceramics fabrication. In these processes, new technique [Sato, 2005] that enables to reduce the amount of organic binder was used. A method [Sato, 2007] to replace organic binder by inorganic binder which is far more cost-effective and environmentally benign is also an alternative technique for "binder removal." A technique called "wet jet milling [Omura, 2006]" was also implemented. Raw ceramic body using jet-milled slurry that had low viscosity and low re-flocculation properties, had very high relative density and showed small shrinkage during sintering. Because of the small shrinkage, the yield rate of the milling process was greatly improved. The TPA approach should explain the effects of abovementioned improvements.

4.3 Quantification of the process improvement

Table 4 shows the value, yield rate, cost and environmental impact of the new process. Improved processes contributed in reducing the cost and environmental impact, and enhancing the value. Effect of these improvements are indicated as shadowed sections in the table. Figure 5 is the TPI graph of the improved process. The solid line shows the improved TPI and the dotted line shows that of the original process. The graph tells us that the TPI of the total process was greatly improved. It is helpful to see that the new process is more environmentally benign, cost-effective and of higher quality.

Table 4. Value, cost, environmental impact of new process

	Segment process							
	Mixture of base materials	Wet jet milling	Injection molding	Reduction of organic binder	Use of inorganic binder	Sintering	Bonding of honeycomb unit	Total
Value of the process (K yen)	8.95	6.44	1.47	2.49	2.49	1.33	0.32	21
Yield rate of the process	0.99	0.95	0.8	0.95	0.95	0.95	0.95	-
Real value of the process (K yen)	8.86	6.12	1.17	2.37	2.37	1.26	0.29	20.1
Environmental impact (kg-CO2/unit)	5	1.2	1	5.6	5.8	9	0.1	
Cost of process (K yen)	5	2.5	1	1.8	0.1	1	1	

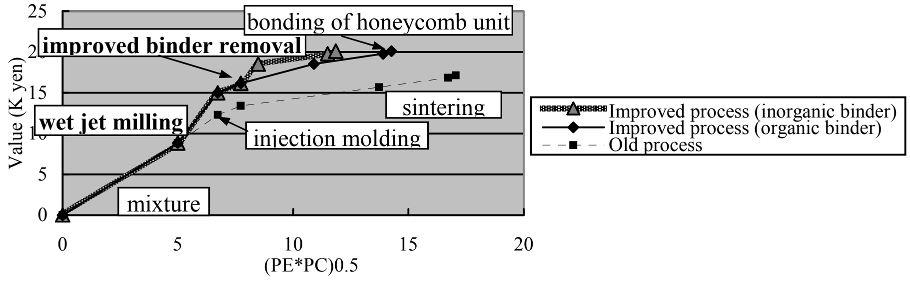

Figure 5. TPI of the improved process

5. Conclusions

In this paper, a new method is proposed for evaluating and designing manufacturing processes by applying TPA. As a result of applying the method to the manufacturing process for a ceramic diesel particulate filter, it was suggested that the process TPI could be improved by replacing certain processes by more efficient processes. An analysis of the actual process improvement in ceramic fabrication explained the fact that "wet jet milling" and "improved binder removal" are effective in reducing the cost and environmental impact, and in enhancing the quality. Precisely speaking, reduction of the amount of organic binder was effective in reducing cost and environmental impact of the process. And replacement of organic binder to inorganic binder was further more effective to enhance the Total Performance of the process. As the result, it is concluded that the proposed design approach is helpful in designing environmentally conscious high quality manufacturing processes.

As future work, it is necessary to consider how quantification of value enhancement is possible when the "yield rate" is same and the quality of the final product is improved. In addition, a totally new process improvement should be analyzed by this approach and put in to practice in order to prove the suggestion is useful in determining new process improvement options.

References

K. Tahara, K. Yamaguchi, M. Sagisaka and A. Inaba, "CO2 Efficiency: A New Evaluation Method of Companies" Environmental Performances," Proc. of the 6th Intn"l Conf. on EcoBalance, Tsukuba, Japan, Oct. 2004, pp.269-270.

S. Kondoh, K. Masui, M. Hattori, N. Mishima and M. Matsumoto, "Total Performance Analysis of Product Life Cycle Considering the Deterioration and Obsolescence of Product Value," Proc. of CARE INNOVATION 2006, Vienna, Austria, Nov. 2006.

M. Ernzer, M. Lindahl, K. Masui and T. Sakao, "An International Study on Utilizing of Design Environmental Methods (DfE) -A pre-study-," Proc. of the Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, IEEE Computer Society, 2003, pp.124-131.

H. Narita, H. Kawamura, T. Norihisa, L. Chen, H. Fujimoto, and T. Hasebe, "Development of Evaluation System of Environmental Burden for Machining Operation (2nd report)," Proc. of JSPE 2004 Autumn Conference, Sept. 2004, pp.111-112. (In Japanese)

K. Akao, "Quality Function Deployment, Productivity Process," Cambridge, M.A., 1990.

S. Kondoh, Y. Umeda, and H. Togawa, "Development of redesign method of production system based on QFD," Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol. 1, No. 1 (2007), pp.181-192.

K. Sato, Y. Hotta, T.Nagaoka, K. Watari, M. Asai and S. Kawasaki, "Mutual Linkage of Particles in a Ceramic Green Body through Photoreactive Organic Binders," Journal of the Ceramic Society of Japan, 113 [10] (2005), pp.687-691.

N. Omura, Y. Hotta, K. Sato, Y. Kinemuchi, S. Kume and K. Watari, "Fabrication of Stable Al2O3 Slurries and Dense Green Bodies Using Wet Jet Milling", Journal of Am. Ceramic Society, 89 [9] (2006), pp.2738-2743.

K. Sato, M. Kawai, Y Hotta, T. Nagaoka and K. Watari, "Production of Ceramic Green Body Using Microwave-Reactive Organic Binder," Journal of Am. Ceramic Society, 90 [4] (2007), pp.1319-1322.

Nozomu Mishima, Ph. D.
Group Leader, Environmentally Conscious Design and Manufacturing Research Group
Advanced Manufacturing Research Institute, National Institute for Advanced Industrial Science and Technology
1-2, Namiki, Tsukuba, Ibaraki JAPAN
Tel.: +81-29-861-7227
Fax.: +81-29-861-7201
Email: n-mishima@aist.go.jp
URL: http://unit.aist.go.jp/amri/