Sustainable Production: Eco-efficiency of Manufacturing Process

29

Nozomu Mishima

Abstract

The term "Sustainable manufacturing" has gained increased attention in recent years. In establishing sustainability in the manufacturing industries, ecodesign of products is important. It is also important to focus on developing and implementing actual manufacturing technologies. Requirements for practical manufacturing technologies include satisfying high quality, low cost, and low environmental impact simultaneously. Environmental issues are very important; however, quality is the key feature in deciding whether the developed manufacturing technologies will be used in the industries. It is not easy to satisfy the three aspects, since there are trade-offs among the three aspects. However, breakthroughs in material technologies and fabrication technologies can be the key factors in making manufacturing technologies industrially feasible. In the first part of this chapter, several new material technologies and fabrication technologies are discussed in order to satisfy high quality, low cost, and low environmental impact simultaneously.

A method called "*total performance analysis* (TPA)" enabled product developer to quantify the value, life cycle cost, and life cycle environmental impact of a product, or its *eco-efficiency*. Since the TPA method can take three aspects of a product into account, it is envisaged suitable method for the evaluation of the *eco-efficiency* of the manufacturing technologies. Thus, to some extent, the TPA method can be applied to evaluate manufacturing technologies in the minimal manufacturing area. Although developing actual manufacturing technologies is the most important part of the minimal manufacturing, recognizing that individual technologies are really "minimal" and industrially feasible is also important. The TPA method was also applied to find an improvement target in the manufacturing processes.

N. Mishima
Graduate School of Engineering and Resource Sceince, Akita University, Akita, Akita, Japan
e-mail: nmishima@gipc.akita-u.ac.jp

J. Kauffman, K.-M. Lee (eds.), *Handbook of Sustainable Engineering*,
DOI 10.1007/978-1-4020-8939-8_41,
© Springer Science+Business Media Dordrecht 2013

In the second half of this chapter, the TPA method was applied to an innovative manufacturing process making ceramic products. In the example, an improved method of making ceramic heat radiation plate made by *silicon nitride* is analyzed and discussed. In the new process, by applying improved manufacturing technology called "*reactive sintering*," the energy consumption and the cost of the total process were greatly reduced. The reduction of the energy consumption is the main contribution in enhancing the *eco-efficiency* in this case. Another example deals with the improvement in *eco-efficiency* which mainly depends on enhancement of product functionality. Throughout the case studies, the "*total performance analysis*" is proven effective in identifying the bottlenecks of manufacturing processes and visualizing the effect of process improvements.

1 Introduction

Recently, AIST (Advanced Industrial Science and Technology) proposed a concept of "minimal manufacturing (Mishima 2011)." Minimal manufacturing is a similar concept to sustainable manufacturing but mainly focuses on developing and implementing actual manufacturing technologies. The core concept is to satisfy three different aspects of innovations in manufacturing technologies which are high quality, low cost, and low *environmental impact* simultaneously in order to implement the developed technologies in practical industries. Although environmental issues are important, quality is the key feature in deciding whether the developed manufacturing technologies will be used in industries. Therefore, in order to determine whether individual technologies in minimal manufacturing can be used in industries or not, it is necessary to take manufacturing quality into account. A method called "*total performance analysis* (TPA)" was proposed by AIST (Kondoh et al. 2008) to quantify the balance of value, cost, and *environmental impact* through the life cycle of products, and the TPA method has been applied to find an improvement target in the manufacturing processes (Kondoh et al. 2007, 2009).

Here, the TPA method was applied to analyze the manufacturing processes of fabricating *silicon nitride* parts. Utilization of *reactive sintering* is effective in decreasing the cost of raw materials and improving the material characteristics (Zhou et al. 2008; Hyuga et al. 2008). These advantages contribute greatly in reducing the total *environmental impact* of the manufacturing process. Since the value of a product is expressed by weighed sum of the quality characteristics, enhancement of the material characteristics is a good solution to enhance the *eco-efficiency* of a product. This chapter shows that TPA is helpful in quantifying the degree of enhancement of the material characteristics and evaluating the degree of minimization of the new manufacturing technologies. Two case studies are presented to prove the effectiveness of the TPA method in evaluating the manufacturing processes.

2 Total Performance Analysis (TPA)

2.1 Basics of TPA

New *eco-efficiency* type index evaluating real *eco-efficiency* of products, by considering product's *utility value*, cost, and *environmental impact*, has been proposed by author's research group. The new index is defined by (29.1) and named total performance indicator (TPI). Since in the existing evaluation indexes the *utility value* is usually a fixed value, it cannot consider the change of the value throughout the product life cycle. The proposed index was the simplest combination of the environmental and economic efficiencies. In the TPI method, because the *utility value* of the product can be expressed by integration of the market (occasional) values throughout the life cycle, it can simulate value decrease due to obsolescence and physical factor as shown in Fig. 29.1.

$$\mathrm{TPI} = \frac{\mathrm{UV}}{\sqrt{\mathrm{LCC}}\sqrt{\mathrm{LCE}}} \tag{29.1}$$

Where

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

2.2 Extension of TPA to the Manufacturing Process Evaluation

Usually, manufacturing processes are combinations of many segment processes, such as material processing, forging, finish machining, etc. In addition, there are many ways to combine processes and boundary conditions. Therefore, it is important to evaluate which manufacturing process is really eco-efficient compared to the alternative options. The total performance of the manufacturing process is

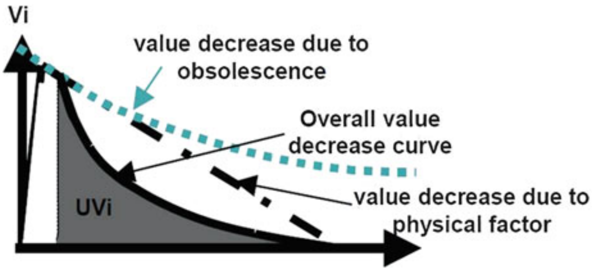

Fig. 29.1 Value decrease through product life cycle

defined by (29.2). The equation expresses the balance of the product value created by the process versus the cost and the *environmental impact* necessary to fabricate the product.

$$\mathrm{TPI}_{\text{process}} = \frac{V}{\sum_{i=1}^{i=n} \sqrt{\mathrm{MCE}_i \cdot \mathrm{MCC}_i}} \tag{29.2}$$

Where

$\mathrm{TPI}_{\text{process}}$: total performance indicator
V: Market price of the product or the part
MCC_i: cost of the ith segment process
n: number of segment processes
MCE_i: environmental impact of the ith segment process

In the manufacturing stage, it is usually difficult to know the life cycle facts of the product such as the obsolescence rate, etc. Thus, in order to simplify the expression, replacing the *utility value* by the market value of the product is proposed. The market value can be measured by market price when the product is commercially available. Then, (29.3) shows the simplified TPI of each segment process.

Numerator "V_i" in (29.3) may vary due to process quality. For example, a manufacturing process with higher profile accuracy may have higher value than a similar manufacturing process with lower quality. Manufacturing quality also has a strong relationship between cost and *environmental impact* of the process. For example, it is known that the cost and *environmental impact* of machining vary due to cutting conditions, and usually they are larger when the manufacturing quality is higher. In addition, for these reasons, in evaluating the manufacturing processes, it is necessary to consider the value of the segment process versus the cost and *environmental impact* concurrently. It is possible to quantify how the target manufacturing process is environmentally effective by calculating $\mathrm{TPI}_{\text{segment}}$ from (29.3).

$$\mathrm{TPI}_{i\text{th segment}} = \frac{V_i}{\sqrt{\mathrm{MCE}_i \cdot \mathrm{MCC}_i}} \tag{29.3}$$

Where

$\mathrm{TPI}_{\text{ith segment}}$: total performance indicator of the ith segment process
V_i: value of the product or part added by the ith segment process

The relationship among the original definition of TPI, TPI of the total manufacturing process, and TPI of the ith segment processes are shown in Fig. 29.2.

2.3 Idea of Improving Manufacturing Process Based on the TPI Value

Only when evaluating the manufacturing processes as an inseparable set of processes, aforementioned equations are sufficient. However, the purpose of the

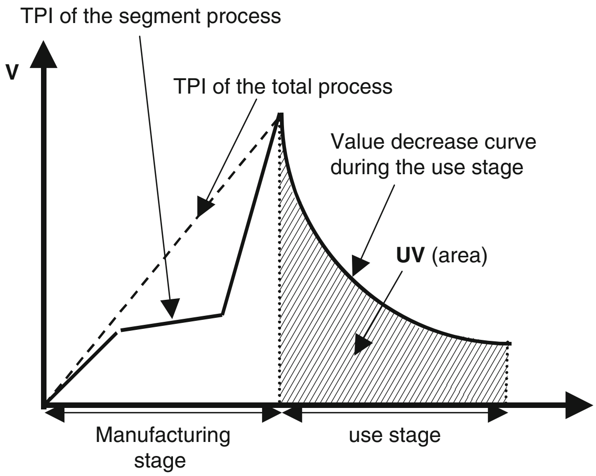

Fig. 29.2 UV, process TPI, and segment TPI

evaluation is to obtain suggestions for the *process improvement*. Thus, it is necessary to evaluate TPI of each segment process and to determine the bottleneck segment process in enhancing TPI of the total manufacturing process.

Figure 29.3 shows the concept of improving TPI of the total manufacturing process by focusing on the bottleneck segment process. The bottleneck process is shown as a segment line with a small slope since it indicates that the segment process has relatively small value and large *environmental impact* and cost. For example, segment process 2 in Fig. 29.3 has a small slope. It means that this segment process does not contribute much in creating the final product value, but it generates relatively large cost and *environmental impact*. In other words, this process is not very efficient in enhancing the manufacturing quality. And therefore, there is a possibility to improve or replace the process. In such case, there are three ways to improve TPI of the total process. They are, “1–1: reduce *environmental impact* of the segment process,” “1–2: enhance the product quality o,” and “2: apply a new combination of processes.” First two focus on the bottleneck process for improvement. The third one is to introduce totally new processes that can take over the total manufacturing processes including the bottleneck segment process. Segment processes A and B in Fig. 29.2 show the schematic image of process replacement by a new combination. All three approaches could enhance process TPI. These three approaches do not mention anything about whether the focused segment process is actually improvable or not.

In order to apply the design evaluation method to an actual process and to ensure its improvement, it is indispensable to collaborate with process engineers who are aware of the problems in their manufacturing process. They usually have deep knowledge about the process and the products manufactured from the process. In addition, as mentioned in the beginning, purpose of this method is to design or redesign environmentally conscious manufacturing processes. Therefore, design

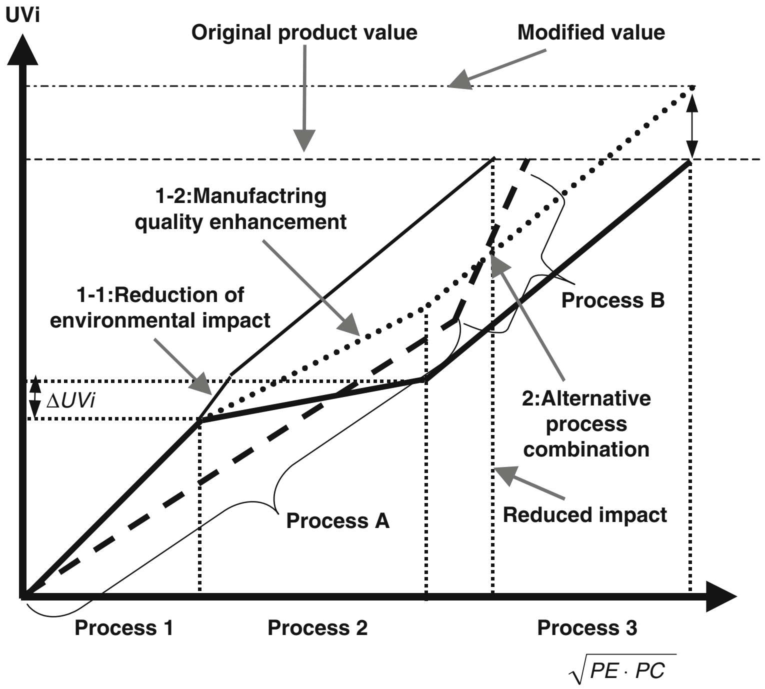

Fig. 29.3 Some methods to improve process TPI

options generating larger *environmental impact* should not be chosen. Because of this reason, knowledge about the actual manufacturing process is necessary to put this approach into practice.

3 Case Studies of Engineering Ceramics

3.1 Manufacturing of Diesel Particulate Filter

To show an actual procedure of the TPA method extended to the manufacturing process (i.e., process TPA) and the improvement of manufacturing processes, a practical example has been examined. Ceramic *diesel particulate filter* (DPF) of which overview is shown in Fig. 29.4 was chosen as a target product. Ceramic DPF are used frequently because of its high thermal endurance and high specific strength (Sato et al. 2005; Omura et al. 2006). The main function of DPF is to eliminate particulate matters generated by diesel combustion. However, the main functional requirement can be separated into more detailed five functional requirements such as "capturing capability of particulate matters," etc. In addition, the five functional requirements can be related to twelve quality characteristics. Defined functional

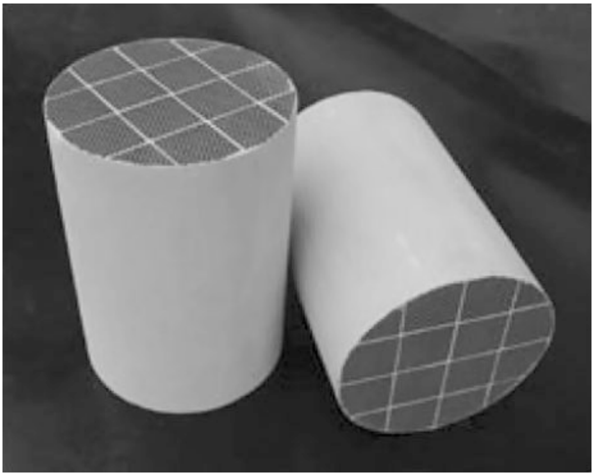

Fig. 29.4 Example of a ceramic diesel particulate filter

requirements and quality characteristics are shown in Table 29.1. Price of the filter unit is assumed to be 20,000 yen.

3.2 Functional Requirements of DPF

Applying the QFD method (Akao 1990; Kondoh et al. 2007), it is possible to clarify importance of each functional requirement of a DPF. Five functional requirements (FR) and twelve quality characteristics of the filter have been set. Table 29.1 shows the importance of each functional requirement to the customers. It also indicated allocation of each functional requirement to the defined quality characteristics. By considering the importance of each FR, it is possible to determine the value of FRs among the total value of the product (20,000 yen). The chosen FRs are all important. In other words, only important functional requirements were chosen. Therefore, the analysis suggests that the value of every FR occupies one fifth of the total value of the DPF.

3.3 Quantification of Quality Characteristics

The second step of the analysis is to know the contribution of each segment process to the value creation. By identifying the relationship between each segment process composing of the total manufacturing process and quality characteristics, it is possible to calculate the value of the segment processes. The total manufacturing process of the DPF was divided into six segment processes. They are "mixture," "*ball milling*," "injection molding," "*binder removal*," "*sintering*," and "bonding of honeycomb unit." Table 29.2 shows the calculation result of the process value.

Table 29.1 Relation between functional requirements and quality characteristics of a ceramic DPF

		Functional requirements					
		Capturing capabilit of particulate matters	Fuel loss due to pressure loss	Fuel loss due to reproduction	Product longevity	Reliablity (crack-free)	Total
Importance of functional requirements		9	9	9	9	9	54
Value of functional requirements (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				18
	Specific heat capacity			9			9
	Uniformity of distribution of pores	3	3				6
	Average diameter of pores	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 relations with functional requirements	33	15	12	21	36	108

"Value of the segment process" in Table 29.2 was calculated by allocating value of each functional requirement corresponding to the strength of the relation shown in Table 29.1. "*Environmental impact* of the segment process" was estimated by

Table 29.2 Relation between quality characteristics and manufacturing (segment) processes

		Value of quality characteristics (kJPY)	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 distribution of pores	1.2	1	3	3	3	1		11
	Average diameter of pores	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 allocated to segment process (k JPY)		8.95	5.72	1.38	2.41	1.25	0.29	20
	Yield rate of the process		0.99	0.6	0.8	0.95	0.95	0.95	-
	Real value of the process (k JPY)		8.86	3.43	1.1	2.29	1.18	0.28	17.1
	Estimated environmental impact of the segment process (kg-CO2/unit		5	1	1	8	9	0.1	
	Actual cost of the segment process (k JPY)		5	3	1	4.5	1	1	

measuring energy consumption and material consumption. "Cost of the segment process" is based on the actual cost of the energy and materials used in the prototype process.

3.4 Quantification of the Segment Manufacturing Processes

As indicated in Table 29.2, the values of the quality characteristics are calculated first. The result shows that several characteristics such as "pore rate," "specific heat capacity," etc. occupy relatively large portion of the value. Therefore, it is assumed that a segment process contributing to achieve these quality characteristics has a high value.

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 does affect following process. For example, ball-milled slurry often has rather high viscosity and causes relatively big shrinkage during "*sintering*." Although the viscosity of the slurry will be meaningless after "*binder removal*," it strongly affects the quality of "*sintering*" and mechanical properties of the product. It is necessary to consider these interactions between segment processes. In order to express the fact that quality of the segment process affects next segment process, "yield rate" is introduced. In the DPF example process, "*ball milling*" has relatively low yield rate. It means 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 Table 29.2 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 chapter is to introduce a procedure to evaluate total performance of the manufacturing process and obtain suggestions for the *process improvement*, showing only the example of the improvement should be sufficient. Therefore, value, *environmental impact* and cost were roughly assumed. By using the calculated value, assumed *environmental impact*, and cost, TPI of segment processes can be calculated.

3.5 Analysis of the Total Manufacturing Process

TPI graph can be drawn using the value, cost, and *environmental impact* of the manufacturing process. Figure 29.5 is the TPI graph of the original manufacturing process of the DPF. The solid line indicates unadjusted value after the corresponding segment processes. The dotted line shows adjusted value when interactions between segment processes are considered by introducing "yield rate." A slope of a segment line shows TPI of the corresponding segment process. A slope of the line connecting between the starting point and the endpoint of the lines indicates TPI of the total process. Comparing to the TPI of the total process, segment processes "*binder*

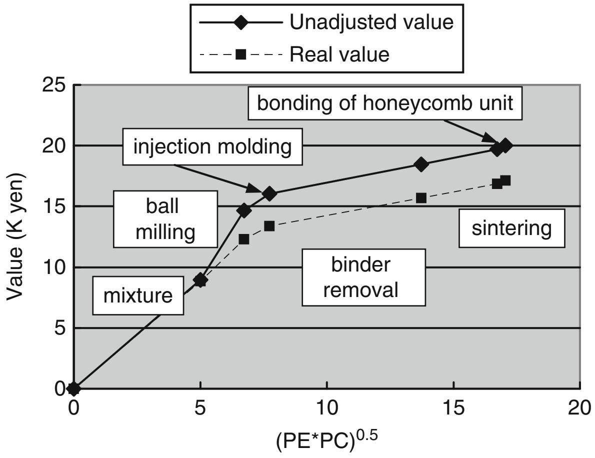

Fig. 29.5 TPI of the manufacturing process of a DPF

removal" and "*sintering*" have lower TPI, and the other processes have relatively higher TPI. This is because "*binder removal*" and "*sintering*" need temperature increase of the material using a furnace, which consumes large amount of electricity. In addition, "*binder removal*" emits hazardous substances due to organic binder material. Cost of elimination of the substances is considered in the cost of the segment process.

3.6 Analysis of the *Process Improvement*

Improvement of the ceramic DPF manufacturing process is an ongoing research topic. Several methods to enhance the performance of the process or reduce the process time have been already investigated, without using the design method described here. The purpose of using the DPF production process as an example is to ensure that the design approach does not contradict with the process engineer's knowledge and to show that it is able to simulate *process improvement* procedure and the effect of the improvement as well. Therefore, it is necessary to compare the TPI of the old process with that of the improved process and quantify the effect of the *process improvement*.

In AIST, new manufacturing processes to make alumina ceramic parts have been proposed for the significant enhancement of the manufacturing speed and ultimate improvement of the productivity of ceramic fabrication. A group of these related new processes is called compact process of ceramic fabrication. In the new processes, a new technique (Sato et al. 2005), which enables the reduction of the amount of organic binder, was used for "*binder removal*." In the new fabrication process, a technique named "*wet jet milling*" which can totally replace "*ball milling*" was also implemented. Raw ceramic body using jet-milled slurry which

Table 29.3 Process value, cost, and environmental impact of the new process

	Segment process						
	Mixture of base materials	Wet jet milling	Injection molding	Improved binder removal	Sintering	Bonding of honeycomb unit	Total
Value of the process (K yen)	8.95	6.44	1.47	2.49	1.33	0.32	21
Yield rate of the process	0.99	0.95	0.8	0.95	0.95	0.95	-
Real value of the process (K yen)	8.86	6.12	1.17	2.37	1.26	0.31	20.1
Environmental impact of the process (kg-CO_2/unit)	5	1.2	1	5.6	9	0.1	
Cost of the process (K yen)	5	2.5	1	1.8	1	1	

had low viscosity and low reflocculation property had very high relative density and showed very small shrinkage during *sintering*. Because of small shrinkage, yield rate of the milling process will be greatly improved. A new fabrication procedure with these new processes was named "compact process." As a result of applying "compact process," both "*ball milling*" and "*binder removal*" were replaced by more environmentally benign processes. The TPA approach should be able to explain the effect of the improvement and to suggest the next target for the process renovation.

Table 29.3 shows the value, yield rate, cost, and *environmental impact* of the improved manufacturing process. As it was mentioned earlier, "*ball milling*" was replaced by "*wet jet milling*." "*Binder removal*" segment process was improved to reduce the amount of organic binder consumed, which contributed to the reduction of the cost and *environmental impact* of the segment process. These improvements are indicated as shadowed area in Table 29.3. Value of the other processes was also improved. Since the yield rate of "jet milling" is high, value of every process after "jet milling" was also enhanced. Figure 29.6 is the TPI plot of the improved process corresponding to the improved values, costs, and *environmental impact*s in Table 29.4. The solid line corresponds to the TPI of the improved process, and the dotted line shows TPI of the original process shown in Fig. 29.5

The effect of "*wet jet milling*" and "improved *binder removal*" were simulated in the TPI plot. It tells us that the TPI of the total manufacturing process was

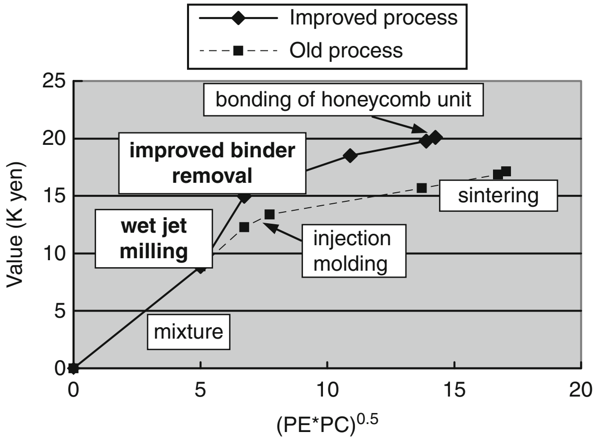

Fig. 29.6 TPI of the improved process

Table 29.4 Importance and value of the functional requirements

		Importance for customers = u_i	Importance (ratio) = u_i/T	Value of FR(kJPY) = FRV_i
FR0	Heat radiation capability	10	0.29	1.2
FR1	Hard-to-failure	5	0.14	0.6
FR2	Electric insulation capability	10	0.29	1.2
FR3	Smooth and parallel surface	5	0.14	0.6
FR4	Resistance capability against atmosphere	5	0.14	0.6

greatly improved. It is helpful to see that the new manufacturing process was more environmentally benign and cost-effective and had higher quality than the conventional manufacturing process. Without calculating the TPI, it is difficult to know the improvement in cost, *environmental impact*, and quality simultaneously. The analysis also pointed out that next improvement target is "*sintering*" since theprocess has large *environmental impact*. In fact, improvement of "*sintering*" by using microwave (Sato et al. 2007) has been proposed already.

3.7 Manufacturing of *Heat Radiation Plate*

To show an actual procedure of the process TPA and improvement of a manufacturing process, a practical example has been examined. A ceramic *heat radiation plate* for power-integrated circuits (ICs) of which overview is shown in Fig. 29.7 was chosen as the target product. Ceramic radiation plates are used frequently because of its high thermal endurance, high specific strength, and high resistance to wear. The main function of a radiation plate is to radiate heat efficiently. The main functional requirements can be separated into more detailed five functional requirements such as "heat radiation," "electric insulation capability," among others. In addition, the five functional requirements are related to eight quality characteristics that are equivalent to material characteristics. Defined functional requirements and quality characteristics are shown in Table 29.4. Price of the *heat radiation plate* is assumed to be 4.2k JPY.

3.8 Consideration of the Functional Requirements

Like the first case study, by applying the QFD method, it is possible to clarify the importance of each functional requirement of a *heat radiation plate*. Five functional requirements (FR) were set. Table 29.4 shows how each functional requirement is important to the customers. It also indicates the calculated price of each functional requirement. Total price of the product (assumed to be 4.2 k JPY/kg) was allocated to the functional requirements corresponding to the importance of FRs. The value of each functional requirement can be calculated based on (29.4).

$$\mathrm{FRV}_i = V \cdot (u_i / T) \tag{29.4}$$

Where

FRV_i: value of the ith functional requirement
V: value of the product
u_i: importance of the ith FR
T: sum of the importance of all functional requirements

3.9 Quantification of the Quality Characteristics

The second step of the analysis is to determine the contribution of each segment process to the monetary value of each quality characteristics. By identifying the relationship between segment processes of the total process and the quality characteristics, it is possible to calculate the value of the segment processes. The total manufacturing process was divided into six individual processes. The value of each segment process is expressed by (29.5). Table 29.5 shows the results of the calculation of the segment process value.

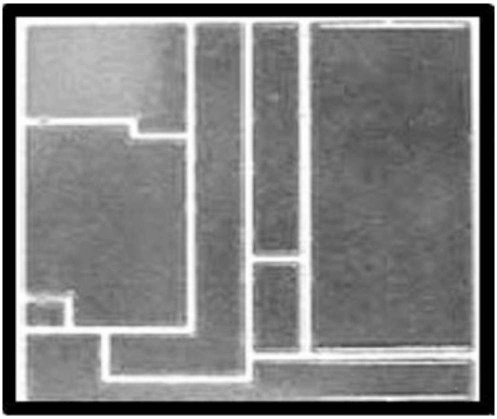

Fig. 29.7 Example of a ceramic heat radiation plate

$$\mathrm{QV}_k = \sum_{i=1}^{n} V_i \cdot (w_{i,k}/T_i) \tag{29.5}$$

Where

QV_k: value of the kth quality characteristics
n: number of the functional requirements
V_i: value of the ith FR
$w_{i,k}$: importance of the kth quality characteristics on the ith FR
T_i: sum of the importance of all the quality characteristics on the ith FR

3.10 Quantification of the Manufacturing Process Value

The third step of the analysis is to determine the contribution of each segment process to the realization of the quality characteristics of the product. Like the first example, the value of each segment process is calculated for the six segment processes of the manufacturing of a ceramic *heat radiation plate* including "material supply," "mixture," "sheet forming," "*binder removal*," "*sintering*," and "grinding." Table 29.6 shows the result of the calculation of the process value based on (29.6).

$$\mathrm{PV}_j = \sum_{k=1}^{m} \mathrm{QV}_k \cdot (x_{j,k}/S_k) \tag{29.6}$$

Where

PV_j: value of the jth segment process
$x_{j,k}$: importance of the kth quality characteristics on the jth segment process

Table 29.5 Value allocation to the quality characteristics

		Functional requirements					
		Heat radiation capability	Hard-to-failure	Electric insulation capability	Smooth and parallel surface	Resistance capability against atmosphere	Value of quality characteristics (kJPY) = QV_k
Value of FR (kJPY) = FRV_i		1.2	0.6	1.2	0.6	0.6	4.2
Quality characteristics of DPF	Heat conductivity	10					1.2
	Mechanical strength		10		1	1	0.37
	Fracture toughness		10		1	1	0.37
	Insulation resistance			10		1	0.64
	Dielectric breakdown strength			10		1	0.64
	Surface flatness				10		0.27
	Surface roughness				10		0.27
	Corrosion resistance					10	0.43
	Sum of importance of all the quality characteristic on the ith FR = T_i	10	20	20	22	14	

S_k: sum of importance of the kth quality characteristics on the jth segment processes

m: number of quality characteristics

Table 29.6 Relation between quality characteristics and manufacturing processes

			Segment process						
		Value of quality characteristics= QV_k	Material supply	Mixture	Sheet forming	Binder removal	Sintering	Grinding	sum of importance of the kth quality charactersitics on the jth segment processes =S_k
Quality characteristics of DPF	Heat conductivity	1.2	10	3	0	0	3	0	16
	Mechanical strength	0.37	3	3	1	3	10	0	20
	Fracture toughness	0.37	3	3	1	3	10	0	20
	Insulation resistance	0.64	10	3	0	3	3	0	19
	Dielectric breakdown strength	0.64	10	3	0	3	3	0	19
	Surface flatness	0.27	1	3	10	0	1	10	25
	Surface roughness	0.27	1	3	0	0	1	10	15
	Corrosion resistance	0.43	10	1	1	1	3	3	19
	Value of the jth segment process (kJPY) = PV_j		1.80	0.64	0.17	0.34	0.89	0.36	

Table 29.7 Environmental impact and cost of the segment manufacturing processes

	Segment process						
	Material spply	Mixture	Sheet forming	Binder removal	Sintering	Grinding	Total
Value of the process (kJPY)	1.80	0.64	0.17	0.34	0.89	0.36	4.2
Environmental impact of the process (kg-CO_2/kg)	5	0.2	0.1	3	5	0.5	13.8
Cost of the process (kJPY)	1.1	0.4	0.8	0.2	0.6	0.8	3.9

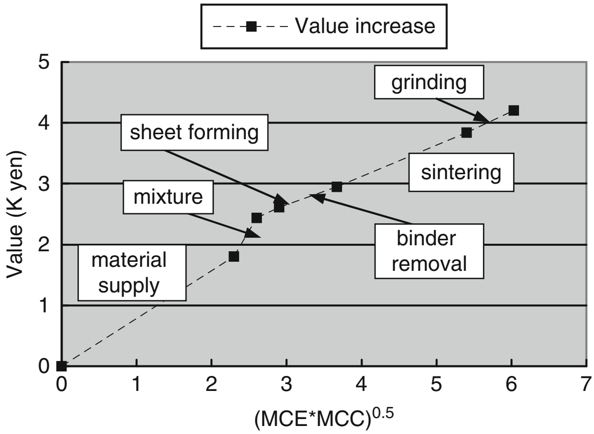

Fig. 29.8 TPI of the original manufacturing process

3.11 TPI-Based Analysis of the Segment Manufacturing Process

To calculate the TPI defined by (29.3) of each segment process, it is necessary to quantify the cost and *environmental impact* of each segment process as well. Table 29.7 shows the estimated cost and *environmental impact* of the segment manufacturing processes based on the information from the manufacturing engineers. The cost and *environmental impact* include those of the machines. Figure 29.8 is the TPI plot of the original manufacturing process of the ceramic *heat radiation plate*. Each segment line indicates the value after the corresponding segment processes. Slope of a segment line shows TPI of the corresponding segment process. If a line is illustrated by connecting the starting point to the endpoint of the segment lines, the slope of the line indicates TPI of the total process.

3.12 *Process Improvement*

Improvement of the *silicon nitride* manufacturing process is an ongoing research topic. Several methods to enhance the performance of the process or reduce the process time have been investigated (Zhu et al. 2004). The series of new processes to make *silicon nitride* products is called sintered reaction-bonded *silicon nitride* (SRBSN). In the new manufacturing process, more inexpensive silicon powder than *silicon nitride* powder is used, because the *silicon nitride* structure is directly formed during the *sintering* process with chemical reactive process. It results in reduction of the cost and the *environmental impact* of “material supply” to the original process. Contrarily, the cost and *environmental impact* of the new “*sintering*” process increase. Costs and *environmental impact*s of the other processes remain unchanged.

Table 29.8 Improvements in the quality characteristics by ratio

	Heat conductivity	Mechanical strength	Fracture toughness	Insulation resistance	Dielectric breakdown strength	Surface flatness	Surface roughness	Corrosion resistance
SSN	1	1	1	1	1	1	1	1
Improved (SRBSN)	1.2	0.9	1	2.0	2.0	1	1	1.1

In addition, by using this process and inputting suitable additives, material characteristics can be greatly improved. It has been reported (Zhu et al. 2006; Zhou et al. 2008) that heat conductivity, insulation resistance, and dielectric breakdown strength of the product are greatly improved compared to the conventional sintered *silicon nitride* (SSN). On the other hand, mechanical strength slightly decreases. Table 29.8 shows the predicted or reported improvements in the quality characteristics by normalizing the original value to 1.

In quantifying the value enhancement due to improvements in the quality characteristics, it was assumed that the value of each quality characteristics is linear to the corresponding specification. For example, the value of "new" heat conductivity is calculated to be 1.4 k JPY, since it will be 1.2 times of the original value 1.2 k JPY. Table 29.9 shows the value of the improved quality characteristics by multiplying the ratio shown in Table 29.8 to the value of each quality characteristics of the conventional process in kJPY.

Finally, Table 29.10 shows the value, cost, and *environmental impact* of the improved manufacturing process. Figure 29.9 is the TPI plot of the improved process reflecting Table 29.10. Comparison of TPI of the old process and of the new process suggested that material composition is the most important consideration. The new "*sintering*" process appears worse than the old process. However, it is inseparable with the new "material supply." Figure 29.9 indicates that efficiency of the total manufacturing process was greatly improved. It also suggests that further improvement should be the optimization of the *sintering* conditions in order to make the new *sintering* process more efficient.

Table 29.9 Improvements in the quality characteristics by value

	Heat conductivity	Mechanical strength	Fracture toughness	Insulation resistance	Dielectric breakdown strength	Surface flatness	Surface roughness	Corrosion resistance
SSN	1.2	.37	.37	.64	.64	.27	.27	.43
SRSBN	1.4	.33	.37	1.3	1.3	.27	.27	.47

Table 29.10 Value, environmental impact, and cost of the improved segment manufacturing processes

	Segment process						
	Material spply	Mixture	Sheet forming	Binder removal	Sintering	Grinding	Total
Value of the new process (kJPY)	2.62	0.89	0.17	0.53	1.12	0.36	5.69
Environmental impact (kg-CO_2/kg)	1	0.2	0.1	3	7	0.5	11.8
Cost (kJPY)	0.2	0.4	0.8	0.2	1.6	0.8	4.0

4 Summary

A new method to evaluate manufacturing processes by applying TPA was introduced. In the first example, the method was applied to analyze a manufacturing process fabricating ceramic *diesel particulate filter*. The analysis result suggests that there is a room for improvement of the $TPI_{process}$ by replacing processes

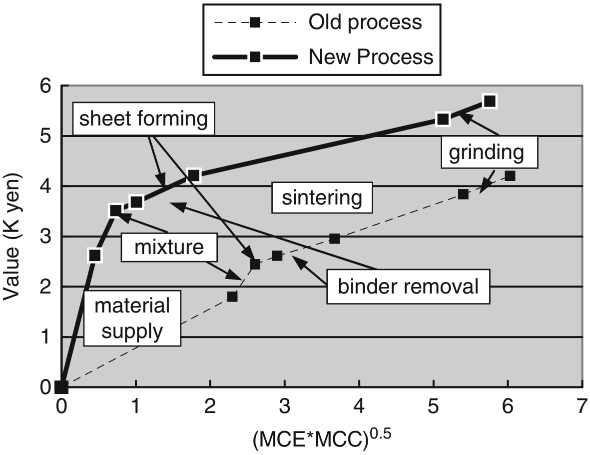

Fig. 29.9 TPI of the improved process

by more efficient processes. Analysis of the actual *process improvement* in the ceramic fabrication revealed that "*wet jet milling*" and "improved *binder removal*" are effective in reducing the cost and *environmental impact* and in enhancing the quality of the ceramic fabricated. The analysis also indicated that next target for improvement is "*sintering*." It is concluded that the process TPA design approach is helpful in designing environmentally conscious and high-quality manufacturing processes.

However, in the first example, the effect of manufacturing *process improvement* in enhancing product quality was not quantified well. Therefore, in the second example, the evaluation method was applied to a new example which is a manufacturing process of a *heat radiation plate* made by *silicon nitride*. In this example, by implementing new manufacturing technology, material characteristics are greatly improved. The new material is called sintered reaction-bonded *silicon nitride* (SRBSN). Total value increase was calculated based on an assumption that the value of each quality characteristics is linear to the improvement of the specification. Using these data, efficiency of the improved manufacturing process was compared with that of the old process. From this, it was found that the new manufacturing process increased *eco-efficiency* of the manufacturing process by more than 40%.

References

K. Akao, *Quality Function Deployment* (Productivity Process, Cambrige, 1990)
H. Hyuga et al., Mater. Lett. **62**, 3475 (2008)
S. Kondoh et al., J. Adv. Mech. Des. Syst. Manuf. **1**(1), 181 (2007)
S. Kondoh, K. Masui, M. Hattori, N. Mishima, M. Matsumoto, Int. J. Prod. Dev. **6**(3/4), 334 (2008)
S. Kondoh et al., Int. J. Autom. Technol. **3**(1), 56 (2009)

N. Mishima, Journal of Japan society for Precision Engineering, **77**(3), 245(2011). (In Japanese)
N. Omura et al., J. Am. Ceram. Soc. **89**(9), 2738 (2006)
K. Sato et al., J. Ceram. Soc. Jpn. **113**(10), 687 (2005)
K. Sato et al., J. Am. Ceram. Soc. **90**(4), 1319 (2007)
Y. Zhou et al., Int. J. Appl. Ceram. Technol. **5**(2), 119 (2008)
X.W. Zhu et al., J. Mater. Res. **19**(11), 3270 (2004)
X.W. Zhu et al., J. Am. Ceram. **89**(11), 3331 (2006)