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REDESIGN METHOD OF MANUFACTURING TECHNOLOGIES BASED ON ENVIRONMENTAL PERFORMANCE EVALUATION

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ABSTRACT
To achieve sustainable society, many efforts in reducing environmental impact of manufacturing have been tried. However, for engineers, enhancing manufacturing quality has long been the most significant goal. Therefore, to evaluate environmentally consciousness of manufacturing technologies, it is necessary to consider manufacturing quality. For the purpose, we have proposed a new indicator to evaluate products and manufacturing processes named "total performance indicator (TPI)." TPI shows a balance of manufacturing quality versus environmental impact and cost of the manufacturing system. The bottleneck process in enhancing product quality can be clarified, by calculating TPI of each process. This paper analyses an actual product and allocates quality characteristics to functional requirements of the product. Then, it quantifies the contribution of each process in creating the product value. A process doesn't contribute much in creating value and generating considerable environmental impact and cost should be improved. It is shown that a designer can evaluate and redesign manufacturing technologies, based on the result of this TPI approach.

Keywords: Environmental impact, manufacturing technology, manufacturing quality, redesign, total performance indicator

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 [1]." 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 [2] (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 and manufacturing facilities. 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 EVALUATION INDEX FOR MANUFACTURING

Usually manufacturing process of an actual product is not so simple. Most of the processes are combinations of many segment processes, such as material processing, forging, rough machining, finish machining, surface polishing, etc. In addition, there many ways to combine processes and boundary conditions. Therefore, it is very important to evaluate the manufacturing process is really environmental conscious comparing to alternative manufacturing options.

2.1 Definition of the index

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 [3]. 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.

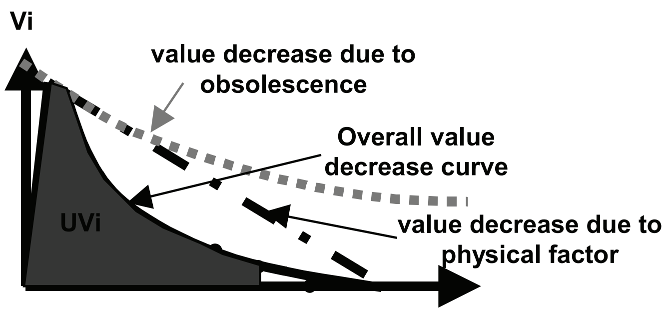

Figure 1. Value decrease throughout product lifecycle

2.2 Extension of the index to manufacturing system evaluation

It is important to take manufacturing quality into account to evaluate whether the manufacturing technology is really environmentally benign. Since the purpose of manufacturing is achieving a certain product quality, low quality process will not be used. Or, more energy, resource, time and money will be used in order to achieve the required quality. That is the reason why design engineers and manufacturers have concentrated in improving the quality and reducing cost of manufacturing. They might not accept an indicator that does not evaluate cost and functionality, properly. So, the evaluation method should be able to quantify 'high quality of manufacturing,' which is a very qualitative expression. The idea of TPI of manufacturing technology is based on product TPI. To evaluate the performances of manufacturing technologies, the same idea can be applied. We define the total performance of the manufacturing technology 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. Unlike the equation (1), instant value V is used instead of UV which is an integral of V through the product lifecycle. Because, as the first step to evaluate the manufacturing processes, we ignored the life length of the product and focused on the peak value of the product created by the corresponding manufacturing processes. The next equation (3) shows a more detailed expression of (2).

$$TPI_{mfg} = \frac{V}{\sum_{i=1}^{i=n} \sqrt{MCE_i \cdot MCC_i}} \quad (2)$$

V: Peak value of the product
TPI_{mfg}: Total performance indicator of the manufacturing technology
MCi: Cost of a segment process including machine cost, labor cost, etc.
MEi: Environmental impact of a segment process including impact of machines, energy, etc.
n: Number of processes

$$TPI_{mfg} = \frac{V}{\sum_{i=1}^{i=n} \sqrt{(MC_{mi} + MC_{ci} + MC_{ei} + MC_{li}) \cdot (ME_{mi} + ME_{ci} + ME_{ei})}} \quad (3)$$

MCmi: Cost of the machine corresponds to the segment manufacturing process
MCci: Cost of the consuming materials corresponds to the segment manufacturing process
MCei: Energy (electricity) cost of the corresponding segment manufacturing process
MCl: Labor cost
MEmi: Environmental impact of the machine fabrication corresponds to the segment process
MEci: Environmental impact of the consuming materials corresponds to the segment process
MEei: Environmental impact of the energy (electricity) used in the corresponding process
n: Number of processes
Lt: Average lifetime of the manufacturing system (year)
H: Average operating hours of the system per year
Ti: Process time of the corresponding manufacturing process

The numerator "*V*" 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 [4] and usually they are larger when the manufacturing quality is higher. In addition, for these reasons, in evaluating manufacturing processes, it is necessary to consider manufacturing quality versus cost and environmental impact simultaneously. In detail, by calculating the abovementioned (3), we can quantify how efficient the target manufacturing technology is.

2.3 Concept of redesigning a 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.

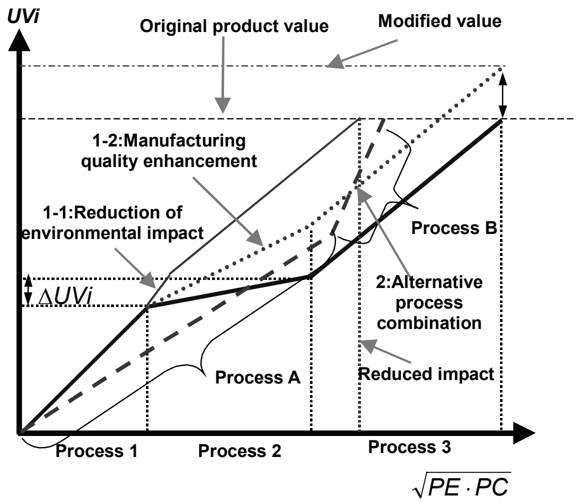

Figure 2. Methods for improving process TPI

3. EXAMPLE OF MANUFACTURING TECHNOLOGY EVALUATION

3.1 Target product for analysis

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.

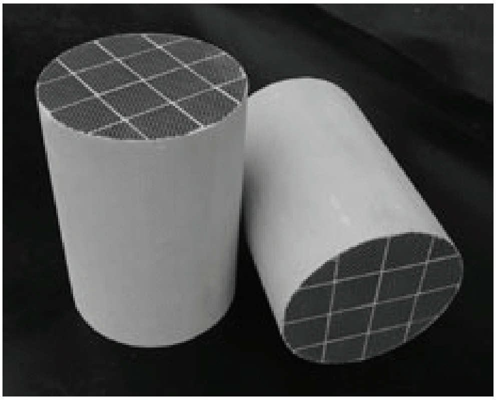

Figure 3. Example of ceramic DPF

3.2 Allocation of product value to functional requirements and quality characteristics

Applying QFD [5], [6], 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 ceramic DPF.

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

		Functional requirements					
		Capability of particulate	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	45
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 moulding	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

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 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, real values of the segment manufacturing processes were estimated by assuming yield rates to all the processes. The yield rates were roughly estimated based on the knowledge of manufacturing engineers in this field.

3.4. Consideration of manufacturing facilities

Value of each segment manufacturing process has been calculated in the former section. As the next step, it is necessary to quantify cost and environmental impact of each process. In the manufacturing processes, not only the method but also the kind of facility used, is also very important. Simply speaking, using small machines versus using large machines is very different, in respect of cost and environmental impact. So, manufacturing facilities should be considered in evaluating the total manufacturing technologies. In other words, the purpose of the evaluation is to determine what product should be made by which facility through which manufacturing process. Therefore, machine cost, material cost, energy cost and labour cost should be considered by the term “cost.” And environmental impact of machine, manufacturing processes, material of the products and energy should be all totalled. To calculate the real cost and impact of each process, it is necessary to know the average process time. Machine cost of the processes can be calculated by allocating initial cost of the machine to the corresponding process time in which the machine is under operation, by assuming the length of the life of the manufacturing facilities. Next, Table 3 shows material cost, energy cost, environmental impact due to materials, and impact of energy usage, used in the segment manufacturing processes shown in Table 2. Table 4 shows rough estimations of costs of the machines and the process time of corresponding manufacturing processes. By assuming that the lifetime of manufacturing facility is 10 years and the facility is operated 200 days per year, 8 hours per day, it is possible to distribute the machine costs to each process. Then, we roughly assumed 100 units can be fabricated by one batch process. It means that the maximum system throughput of the facility is 100 units per 4 days. Therefore, whatever the process time is, throughput of the system is 25 units per day. In addition, all the processes can be controlled by one operator. Because "binder removal" and "sintering" are operated in the same furnace continuously, by changing the temperature, the machine cost and environmental impact of those processes were divided by 2. Labour cost is assumed to be 5000K JPY per year. The cost was allocated to bonding process, because other processes are operated automatically. Sum of machine cost and labour cost for the corresponding process is shown in Table 4. Table 5 shows the environmental impact of the manufacturing facilities corresponding to the processes. Environmental impacts of the machines were calculated using inter-industry relations table. CO-2 emission of the machine fabrication is assumed to be 0.72 t-C (1.98t-CO2)/mill. JPY. From Tables 3 to 5, it is resulted, material and energy play large roles in respects of cost and environmental impact. Finally, Table 6 shows the total cost and environmental impact of each segment process to fabricate one DPF unit.

Table 3. Material and energy necessary for the segment processes (per unit)

Manufacturing process	Material and energy cost (K JPY)	Environmental impact of material and energy (kg-CO2)
Material mixing	5	5
Ball milling	3	1
Moulding	1	1
Binder removal	4.5	8
Sintering	1	9
Bonding of units	1	0.1

Table 4. Cost of manufacturing facilities and labour

Manufacturing process	Process time	Machine cost (K JPY)	Machine (labour) cost per unit (K JPY)
Material mixing	-	-	-
Ball milling	1 day	1000	0.02
Moulding	20 minutes	10000	0.2
Binder removal	2 days	25000	0.5
Sintering	2 days	25000	0.5
Bonding of units	1 day	-	1

Table 5. Environmental impact of manufacturing facilities and labour

Manufacturing process	Environmental impact of machine (kg-CO2)	Environmental impact of machine per unit (kg-CO2)
Material mixing	-	-
Ball milling	1980	0.04
Moulding	19800	0.4
Binder removal	49500	1
Sintering	49500	1
Bonding of units	-	-

Table 6. Total cost and environmental impact of segment processes

	Segment process					
	Mixture of base materials	Ball milling	Injection moulding	Binder removal	Sintering	Bonding of honeycomb unit
Environmental impact of process (kg-CO2)	5.0	1.0	1.4	9	10	0.1
Cost of the process (K yen)	5.0	3.0	1.2	5.0	1.5	2

3.5 Visualization of environmental performance of the manufacturing technology

Using value, cost and environmental impact shown in the table in the former section, 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.

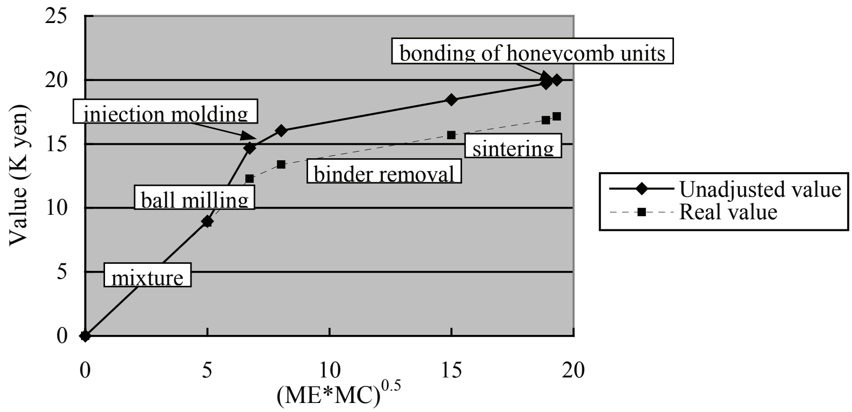

Figure 4. TPI of the manufacturing process of a DPF

4. EVALUATION OF REDESIGNED PROCESS

4.1 Strategies for process redesign

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 Figure.2. 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 moulding" is not very efficient according to Figure.4. 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.

4.2 Analysis of technology 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 analyse actual improvement. New manufacturing processes have been proposed for significant enhancement of manufacturing speed and productivity of ceramics fabrication. In these processes, new technique [7] that enables to reduce the amount of organic binder was used. A method [8] 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 [9]" 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 Visualization of the technology improvement

Table 7 shows the cost and environmental impact due to energy and material usage. Table 8 and 9 shows that of the improved process. Since the improved process requires different milling machine and additional microwave furnace in binder removal process, values of these two processes are different. In this case, the throughput of the facility is about 100units per 2.5 days. Table 10 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. 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 can achieve higher quality.

Table 7. Material and energy necessary for the segment processes (per unit)

Manufacturing process		Material and energy cost (K JPY)	Environmental impact of material and energy (kg-CO2)
Material mixing		5	5
Ball milling		2.5	1.2
Moulding		1	1
Binder removal	Organic	1.8	5.6
	Inorganic	0.1	5.8
Sintering		1	9
Bonding of units		1	0.1

Table 8. Cost of manufacturing facilities and labour

Manufacturing process	Process time	Machine cost (K JPY)	Machine (labour) cost per unit (K JPY)
Material mixing	-	-	-
Ball milling	4 hours	5000	0.06
Moulding	20 minutes	10000	0.13
Binder removal	1 day	35000	0.44
Sintering	1 day	25000	0.31
Bonding of units	1 day	-	0.63

Table 9. Environmental impact of manufacturing facilities and labour

Manufacturing process	Environmental impact of machine (kg-CO2)	Environmental impact of machine per unit (kg-CO2)
Material mixing	-	-
Ball milling	9900	0.12
Moulding	19800	0.25
Binder removal	69300	0.87
Sintering	49500	0.62
Bonding of units	-	-

Table 10. Value, cost, environmental impact of the new process

	Segment process							
	Mixture of base materials	Wet jet milling	Injection moulding	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	1.3	1.3	6.5	6.7	9.6	0.1	
Cost of process (K yen)	5	2.6	1.1	2.2	0.5	1.3	1.6	

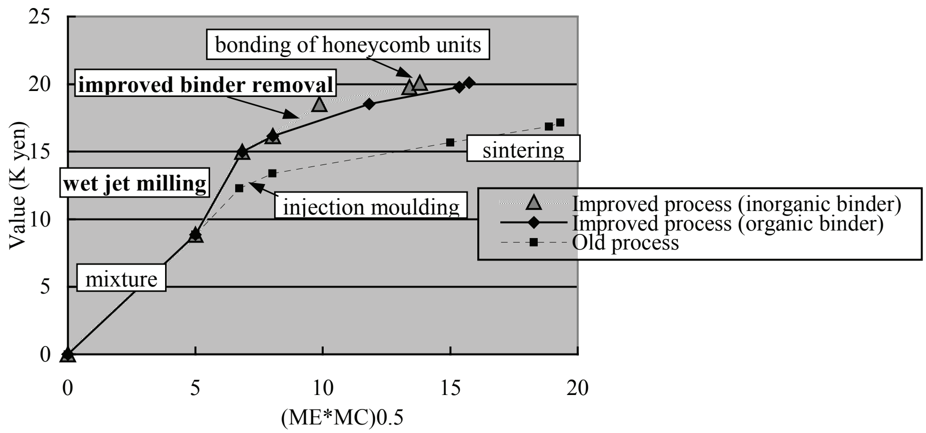

Figure 5. TPI of the improved process

5. CONCLUSIONS

In this paper, a new method was proposed for evaluating and redesigning manufacturing technologies by applying Total Performance Indicator approach. As a result of applying the method to the manufacturing process of a ceramic diesel particulate filter, it was suggested that the TPI of the manufacturing technology 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” were effective in reducing the cost and environmental impact. These improvements also contributed to enhance the manufacturing quality by improving the yield rate which strongly affects the value of the total manufacturing process. Precisely speaking, only in the “wet jet milling,” environmental impact of the process per one DPF unit increased. However, enhancement in system throughput and improvement of yield rate covered this point. In addition, reduction of the amount of organic binder was effective in reducing cost and environmental impact of the total manufacturing system. And replacement of organic binder to inorganic binder was further more effective in enhancing the total environmental performance. As the result, it is concluded that the proposed design approach is helpful in evaluating and redesigning environmentally conscious high quality manufacturing technologies.

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 analysed by this approach and put into practice in order to prove the suggestion is useful in determining new process improvement options. Currently, the evaluation results have been examined only by researchers in ceramics manufacturing field. Thus, most of all, the evaluation result should be tested in industries in order to prove that the proposing method is useful in finding improvement targets in practical manufacturing processes and in suggesting the proper strategy of improvement.

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