INTERNATIONAL DESIGN CONFERENCE - DESIGN 2010
Dubrovnik - Croatia, May 17 - 20, 2010.

APPLICATION OF SUSTAINABLE ASPECTS TO THE SET-BASED DESIGN METHOD

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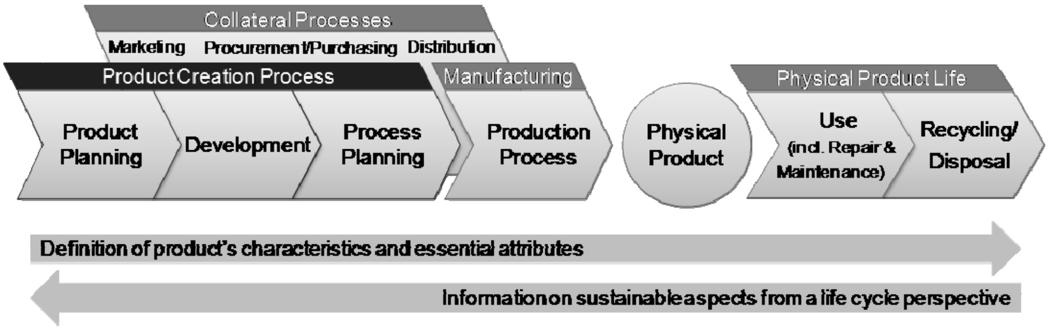
Keywords: sustainable product development, set-based design method, sustainable life-cycle scenario

1. Introduction

The World Commission on Environment and Development defined sustainable development as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [World Commission on Environment and Development 1987] already in the year 1987. The implementation of the concept of sustainable development requires, among other issues, the use of appropriate methods and tools in product creation processes. In the past, various approaches to sustainable product creation primarily address ecological and economical aspects. Social aspects are often neglected, even though products and their processes directly influence the living conditions of today's and future generations. As a result, the product properties which are defined during the process of product creation should support and ensure sustainable development throughout the entire product life cycle [Stark, et al., 2008]. When it comes to a sustainable life cycle, Figure 1 shows the evidence of decision-making at the early phases of design.



Conclusion: Product Creation Process needs appropriate methods and tools in order to develop sustainable (environmentally friendly, economically successful and socially acceptable) products.

Figure 1. The role of the product creation in the entire product life cycle

However, the economical, ecological and social perspectives of sustainability have to be aligned with technical requirements. Since essential attributes and characteristics of products are already determined in the stages of product devleopment, it is necessary to integrate sustainable aspects into the product development process. Nowadays, product developers have to rely on their product knowledge and methods in order to evaluate the impact of design alternatives on the entire product life cycle. But due to increasing product complexity and diversity (e.g. mechatronic systems and Product Service Systems) this mission is rather impossible and one depends on supporting methods and tools [Stark, et al., 2009].

The previous series of our studies have proposed a preference set-based design (PSD) method that can generate a ranged set of design solutions that satisfy multi-objective performances while incorporating designer's preference structure at the early phase of design [Inoue, et al., 2009, 2010]. An approach to sustainable product creation based on the PSD method is presented in this paper. Furthermore, this paper discusses the ability of our proposal to obtain the multi-objective satisfactory solutions not only about technical performances but also about sustainable issues. Finally, to verify the new approach, the PSD method is applied to an alternator.

2. Preference set-based design method (PSD method)

The PSD method consists of four steps, the set representation, set propagation, set modification, and set narrowing, which are described in the following. A detailed description of the PSD method can be found in [Inoue, et al., 2009, 2010].

2.1 Set representation

To capture the designer's preference structure on a continuous set, both an interval set and a preference function defined on this set, which is called the "preference number (PN)", are used. The PN is used to specify the design variables and performance requirements, where any shapes of PN are allowed to model the designer's preference structure, based on designer's knowledge, experience, or know-how. The interval set at the preference level of 0 is the allowable interval, while the interval set at the preference level of 1 is the target interval that the designer would like to meet.

2.2 Set propagation and modification

The set propagation method, which combines the decomposed fuzzy arithmetic with the extended interval arithmetic (*i.e.*, Interval Propagation Theorem, IPT [Finch, et al., 1996]), is proposed to calculate the possible performance spaces which are achievable by a given initial design space. Afterwards, if all the performance variable spaces have the common spaces (*i.e.*, acceptable performance space) between the required performance spaces and the possible performance spaces, there is a feasible subspace within the initial design space. Otherwise, the initial design space should be modified in set modification process.

2.3 Set narrowing

If the overlapping regions between the possible performance spaces and the required performance spaces exist, there are feasible design subspaces within the initial design space. However, if the possible performance space is not the sub-set of the required performance space, there also exist infeasible subspaces in the initial design space that produce performances outside the performance requirement. Then, the next step is to narrow the initial design space to eliminate inferior or unacceptable design subspaces, thus resulting in feasible design subspaces. To select an optimal design subspace out of those feasible design subspaces, robust design decisions need to be made to make a product's performance insensitive to various sources of variations. The present method has been also used to define the possible design space by capturing the designer's preference structure. In addition to the design robustness, we should take into account which one is preferred by the designer. The design preference and robustness are evaluated to eliminate infeasible design subspaces.

2.4 Design metric for design preference and robustness

In engineering design, the designer's design preference and the robustness of design solution are greatly important. A high design preference means that there are large feasible design subspaces within the designer's required performance spaces. On the other hand, design robustness includes the accuracy, convergence and stability of design. A high accuracy of design means that minimizing variations of a performance causes variations of design variables. A high convergence of design means that designers can find the preferable design solution easily and fast. However, a high stability of design means that a low probability of design modification occurs. This study eliminates infeasible design subspaces by evaluating the design preference and robustness.

3. Investigation of sustainability indicators

3.1 Sustainability indicators

In order to consider the sustainability of products, we investigated different officially accepted sustainability indicators. Additionally, we identified which indicators are related to the product development process.

Table 1. Sustainability indicators related to the development process of products

#	Category	Subcategory	Indicator	Country	Year
1	Ecological	Recycling	Amount of recycled and reused wastes	Mexico	2000
2	Ecological	Recycling	Ratio of Waste Recycled	Taiwan	2002
3	Ecological	Recycling	Ratio of reused or recycled waste to total waste	Thailand	2005
4	Ecological	Recycling	Materials recycling	UK	2004
5	Ecological	Recycling	Amount of secondary/ recycled aggregates used compared with virgin aggregates	UK	2004
6	Ecological	Recycling	Waste recycling and reuse	UN	2001
7	Ecological	Chemicals	Prohibited or strictly-restricted chemical substances	Mexico	2000
8	Ecological	Chemicals	Hazardous chemicals, quantity	Sweden	2006
9	Ecological	Chemicals	Regulate prohibited or strictly prohibited chemicals	Taiwan	2002
10	Ecological	Noise	Noise levels	UK	2004
11	Ecological	Resources	Use of renewable energy sources	Finland	2006
1	Economical	Waste generation and management	Harmful waste (kg/person/year)	East Asia	2003
2	Economical	Material use	Material input	Austria	2002
3	Economical	Material use	Energy and raw materials productivity	Germany	2002
4	Economical	Material use	Materials Use per Dollar of Investment	US	2001
5	Economical	Material use	Intensity of material use	UN	2001
6	Economical	Transportation	Mileage	Austria	2002
7	Economical	Transportation	External costs of transport	Austria	2002
8	Economical	Transportation	Traffic-related emissions	Austria	2002
9	Economical	Transportation	Transport emissions (CO_2, CO, PM10, NOx, NMVOC and SO_2)	Denmark	2002
10	Economical	Transportation	Transporting goods, person (ton/km, people/km)	East Asia	2003
11	Economical	Energy use	Energy and raw materials productivity	Germany	2002
12	Economical	Energy use	Energy use Intensity	Taiwan	2002
13	Economical	Energy use	Intensity of energy use	UN	2001
14	Economical	Eco-business	Number of products with eco-label	Austria	2002
15	Economical	Eco-business	Products that were produced under environmental or social standards	Belgium	2005
16	Economical	Eco-business	Feasibility of eco-labels	Taiwan	2002
17	Economical	Business and industry	Labor Productivity in Manufacturing Industry	Taiwan	2002
18	Economical	Eco-performance	Labour productivity	Australia	2006
19	Economical	Eco-performance	Productivity Indicator	France	2004
1	Social	Health	Satisfaction with health	Germany	2002

The National Institute for Environmental Studies (NIES) in Japan has reviewed indicators on sustainable development which were developed by national governments and international organizations, and considered what types of indicators were being used as a database (2006-2008) [NIES, 2009]. This database includes 1,528 listed sustainability indicators, which can be searched by using a web search engine. Furthermore, it covers 26 countries, regions, and international organizations. Using the database, we selected 31 sustainability indicators which are related to the development process of products. Moreover, we categorized these indicators into 3 aspects: ecological, economical, and social aspects as shown in Table1.

Furthermore, we selected two sustainability indicators from Table 1 for further consideration: the CO_2 emissions and the mass of products at a first step. Both indicators are related to all sustainable aspects and can be calculated quantitatively. The carbon dioxide is one of the green house effect gases and relates to climate change. The goal of sustainable development from an ecological perspective is to not increase the emission amount of CO_2. The transportation emission including CO_2 is a very important factor, as it is an economical aspect. If the emission amount of CO_2 increases, the temperature rises, the amount of production of foods decreases and the price of foods are increasing, finally poor nutrition occurs because of the difficulty for people to gain foods. Therefore, CO_2 emissions are related to health as a social aspect. Weight saving of products is related to the CO_2 emissions, the efficiency of transport, and the protection of our natural resourses. In this paper, we can consider only two sustainability indicators (mass and CO_2). However, further sustainability indicators and issues should be considered and added to the evaluation items in the future.

3.2 Evaluation for environmental loads based on LCA

Life cycle assessment (LCA) is a methodology for evaluating environmental loads or an effect extent of products. LCA can evaluate potential environmental loads by calculating the amount of resources, energy, and harmful emissions through the product life cycle.

One of the measures of evaluation in LCA is CO_2 emission. The Japan Vacuum Industry Association (JVIA) has proposed the "JVIA LCA model" which can evaluate the environmental loads of associated equipment of vacuum equipment, e.g. a pump [JVIA, 2009]. This model assists designers in figuring out the environmental loads of manufacturing equipment and inventory analysis for environmental loads at the process of product design. The objective of this model is to get information which is needed for LCA of a product. The model can calculate the inclusive sum of environmental loads at each product life cycle process, such as manufacturing process, using process, maintenance process, reuse process, recycle/disposal process. Moreover, this model can also analyze environmental loads at a portion of product life cycle process.

In this chapter, we explain about the evaluation at recycle/disposal process which has no relationship to the performance at the design process. Environmental loads ($A_{j(a)}$), reduced environmental loads ($A_{j(b)}$), and disposal environmental loads (T) are calculated by the following equations including necessary charge (C_j) and embodied environmental loads intensities (B_j) as shown by Table 2 and Table 3, respectively. Where j is the items for environmental loads (disassembly/segregation/cleaning, sub material, transportation, and incineration) or reduced environmental loads (recycle and reuse).

$$A_j = C_j \times B_j \tag{1}$$

$$T = \sum_j A_{j(a)} - \sum_j A_{j(b)} \tag{2}$$

Whereas T represents the disposal environmental loads [kg], $A_{j(a)}$ is the amount of environmental loads at $j(a)$ [kg]. $A_{j(b)}$ is the amount of reduced environmental loads at $j(b)$ [kg] and C_j is the charge at $j(a)$ or $j(b)$. B_j is the embodied environmental loads intensities at $j(a)$ or $j(b)$.

Embodied environmental loads intensities are defined by "Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables [Nansai, et al., 2002]" by National Institute for Environmental Studies and "Environmental load data of 4000 social stocks for preliminary LCA [NIMS, 2009]" by the National Research Institute for Metals Eco materials research team.

Table 2. Items for calculation of environmental loads

j: item	C_j: necessary charge at j	B_j: embodied environmental loads intensities at j
Disassembly/ Segregation/ Cleaning	Energy [kWh]	Embodied environmental loads intensities for energy [kg / kWh]
Sub material	Charge [kg]	Embodied environmental loads intensities for sub material [kg / kg]
Transportation	Distance [km] × Mass [kg]	Embodied environmental loads intensities for transportation [kg / km · kg]
Disposal	Amount of disposal [kg]	Embodied environmental loads intensities for disposal process [kg / kg]

Table 3. Items for calculation of reduced environmental loads

j: item	C_j: necessary charge at j	B_j: embodied environmental loads intensities at j
Recycle	Mass [kg]	Embodied environmental loads intensities for recycle [kg / kg]
Reuse	Quantity	Embodied environmental loads intensities for reuse [kg / quantity]

3.3 Life cycle scenario design

During the designer's decision making process, different design alternatives are taken into consideration thus life cycle scenarios of possible product futures have to be created in order to meet sustainable issues. Fur this purpose, [Lindow, et al., 2009] describes a systematic approach how sustainable scenarios can be developed. In addition, [Suesada et al. 2007] present a supporting system for a life cycle scenario development. Taking both approaches into consideration, the life cycle strategy for a product can be determined. The life cycle strategy is a combination of different life cycle options of the product and its components (e.g. reuse and recycling, maintenance, Design for X) and its expected life cycle.

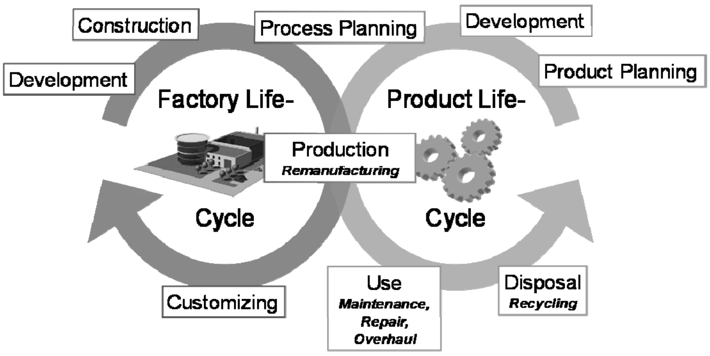


Figure 2. Holistic life cycle approach [Lindow et al. 2009]

The representation of product life cycles is based on the assumption that artificial systems have, in analogy to biological systems, a limited lifespan. Within their lives, products and processes pass through characteristic time periods, which can be divided into distinct phases. However, regarding a fully sustainable product, not only the product life cycle but also the factory life cycle has to be taken into account. A sustainable product is only sustainable if it is manufactured sustainable. Nevertheless, in order to deal with the complexity of real product and factory life cycles a theoretical model has been established. Figure 2 represents a holistic system which takes both life cycles into consideration. Furthermore, the representation of product and factory life cycle as one system shows how closely the various stages of life are interrelated. They correlate and interact with each other e.g. in process planning or production phase [Lindow, et al., 2009].

4. Case study: Application to an alternator

4.1 Setting of design problem

In this paper, a design of an alternator structure is chosen to illustrate the effectiveness of the proposed system for instantaneously obtaining a design set of solutions by proposed PSD calculation system. The parametric CAD model as shown in Figure 3 was created by defining the design parameters which effect the required performances including physical and sustainable aspects. The present study applies the proposed system to the alternator structure by using this CAD model.

The purpose of this design is to define the values of two design variables including a height of rotor coil (= height of stator) (X_1) and a radius of rotor (X_2) as shown in Figure 3.

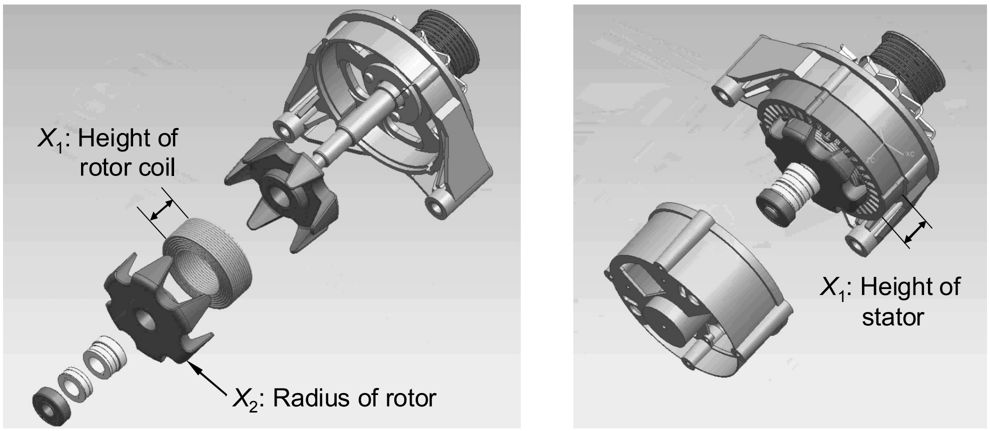


Figure 3. CAD model and design variables of the alternator

The performance requirements include the considerations on physical performance of an alternator, *i.e.*, power (Y_1), mass (Y_2) and on performance for sustainable aspect, *i.e.*, environmental loads: CO_2 emissions (Y_3). The power (Y_1) can be calculated by:

$$Y_1 = \frac{\pi \cdot n_{\text{revolution}}}{30} \cdot I^2 \cdot \mu \cdot n_{\text{layer}} \cdot n_{\text{pole}} \cdot \frac{X_1}{r_{\text{coil}}} \cdot X_2 \tag{3}$$

Whereas $n_{\text{revolution}}$ is the number of revolutions per minute: 2000 rpm, I is current: 70A, μ is magnetic permeability: $2\pi\times10^{-3}$, n_{layer} is the number of layers of rotor coil: 10, n_{pole} is the number of poles of rotor: 12, and r_{coil} is the radius of rotor coil wire 0.25×10^{-3}m. In this study, the values of the parameters except the design variables (X_1 and X_2) are fixed. The mass of each part can be calculated out of the CAD models, e.g. using a CAD-system as NX.

4.2 Evaluation of environmental loads considering a disposal process

Evaluation equations used at this application are based on "JVIA LCA model". This system outputs emission volume of greenhouse effect gas, such as CO_2 [kg] as amount of environmental loads. These amounts for each process of product lifecycle, such as disassembly, segregation, cleaning, sub material, transportation, incineration, recycle, and reuse, are integrated into determinate evaluation result. Equations calculating amount of environmental loads at each process (A_1 - A_6) is shown at equations (4) - (10). And the final evaluation result T is shown at equation (10). Where sub-materials are chemicals used at disassembly process, segregation process, and cleaning process. Concerning transportation process, transportation weight is summation of every component except reuse component on the basis that recycle process is relegated to processor.

A_1 is the amount of environmental loads at disassembly, segregation, and cleaning.

$$A_1[kg] = \sum \left(P_m \times t \times I_p\right) \tag{4}$$

where P_m is electrical power of processing machine [kW], t is used time [h], I_p is embodied environmental loads intensities for utility electrical power [kg/kWh].
A_2 is the amount of environmental loads by sub material.

$$A_2[kg] = \sum \left(M_s \times I_s\right) \tag{5}$$

where M_s is amount of used sub material [kg], I_s is embodied environmental loads intensities at process using sub material [kg/kg].
A_3 is the amount of environmental loads at transportation process.

$$A_3[kg] = (d_t \times M_t \times I_t) + (d_t \times I_f \times f) \tag{6}$$

where d_t is transportation distance [km], M_t is transportation weight [kg], I_t is embodied environmental loads intensities for transport machine [kg/km·kg], I_f is embodied environmental loads intensities for fuel [kg/l], f is fuel consumption [km/l].
A_4 is the amount of environmental loads at incineration process.

$$A_4[kg] = \sum \left(M_i \times I_i\right) \tag{7}$$

where M_i is amount of incinerated material [kg], I_i is embodied environmental loads intensities at incineration process [kg].
A_5 is the amount of reduced environmental loads at recycle process.

$$A_5[kg] = \sum \left(M_c \times I_c\right) \tag{8}$$

where M_c is amount of recycled material [kg], I_c is embodied environmental loads intensities at recycle process [kg/kg].
A_6 is the amount of reduced environmental loads at reuse process.

$$A_6[kg] = \sum \left(N \times I_u\right) \tag{9}$$

where N is number of components, I_u is embodied environmental loads intensities at reuse process [kg/number].

$$T[kg] = (A_1 + A_2 + A_3 + A_4) - (A_5 + A_6) \tag{10}$$

These equations calculate the amount of environmental loads by substitution of model information from 3D-CAD and various constant from database of the embodied environmental loads intensities.

4.3 Life cycle scenarios for the alternator

On the basis of the holistic life cycle approach (see Figure 2), two different life cycle strategies for an alternator (see Figure 3) have been developed. The strategic focus of these scenarios is on the end-of-life (EoL) stage thus the possibilities are remanufacturing, recycling or reuse for each component of the alternator. Due to the complexity and extent of the generation of scenarios, only the results of two scenarios will be described. However, information for the development of possible sustainable futures of each component of the alternator can be extracted.
The alternator is mainly characterized by standardized parts which are connected with each other by standardized interfaces. This allows that parts could be used in different products and/or product

classes. Eventually, standardized interfaces and internationally accepted standards and guidelines allow the manufacturer to globally develop, manufacture and distribute individual parts and assemblies. Once the powertrain reaches EoL it is returned to the manufacturer. Assemblies are partially processed for remanufacturing. According to life prediction sensors are installed in all elements. They remind of inspections and point out eventual failure. In order to design elements for remanufacturing, replacement, modernization and maintenance, shape memory alloys are utilized. Thus, time for disassembly and re-assembly is reduced rapidly. Finally, the whole alternator or at least parts of it are used in other products and last longer than one life. Furthermore, product information is transparently available. According to the product, services in terms of consulting, maintenance, modernization and overhaul are offered over the entire life cycle.

Table 4. End-of-life scenarios for the alternator's parts

Part	Material	EoL - Scenario 1	EoL - Scenario 2
Stator	Steel	Material recycling	Reuse
Rotor coil	Copper C10100	Material recycling	Reuse
Rotor	Iron Cast G25	Disposal (landfill)	Reuse
Drive shaft	Steel	Material recycling	Material recycling
Belt fitting	Aluminum6061	Material recycling	Material recycling
Fan	Steel	Reuse	Reuse
Spacer	Aluminum6061	Reuse	Reuse
Bearing	Rolled steel	Material recycling	Material recycling
Slip ring N	Copper C10100	Material recycling	Material recycling
Slip ring S	Copper C10100	Material recycling	Material recycling

However, Table 4 represents the results of two different life cycle scenarios at the EoL stage. Each component is analyzed and different possible futures are described. In general, when it comes to the EoL, the alternators have to be returned to a collection station. The average distance is 800km and the transportation machine is a heavy duty truck (10t, light oil). To specify this data in the scenario is necessary in order to calculate the environmental load using the PSD method.

4.4 Application of PSD and results

In order to align technical performances with sustainable issues, the PSD method is extended to various sustainable aspects. Due to the high complexity of real sustainable systems, the approach necessitates simplification. We have put the focus on CO_2 emmisions and mass because both factors have economical, ecological and social impacts on the entire product life cycle. Since the calculation is done by a prototypical tool, only the results will be presented in the following.

However, the design set solutions between scenario 1 and scenario 2 are compared to verify how the life cycle scenarios reflect the design solutions. Figure 4 and Figure 5 show the possibile distribution of performances and the ranged set of solutions of design variables, respectively. Moreover, Figure 4 indicates that two types of possibile distributions are limited within the required performances as shown in dotted lines. We can confirm that the power performance in case of scenario 2 is better than the one in case of scenario 1. This result shows that the performance increases when an appropriate life cycle scenario and the importance of the scenario is set. On the other hand, there is a significant difference between scenario 1 and 2 when it comes to CO_2 emissions. Regarding mass and power, the designer's decision would be on an alternator's design alternative according to scenario 1. However, the CO_2 emissions of a design solution according to scenario 2 might change the viewpoint. This means that the designer should design the rotor for reuse and not for material recycling for instance.

Figure 5 indicates that all of the ranged sets of solutions of design variables as shown in solid line are narrowed from the initial preferences of design variables as shown in dotted lines. We can confirm that the design set solution in case of scenario 2 have a wider distribution because scenario 2 fulfills sustainable issues better than scenario 1. These results show that the multi-objective satisfactory design solutions are obtained by our proposed PSD method.

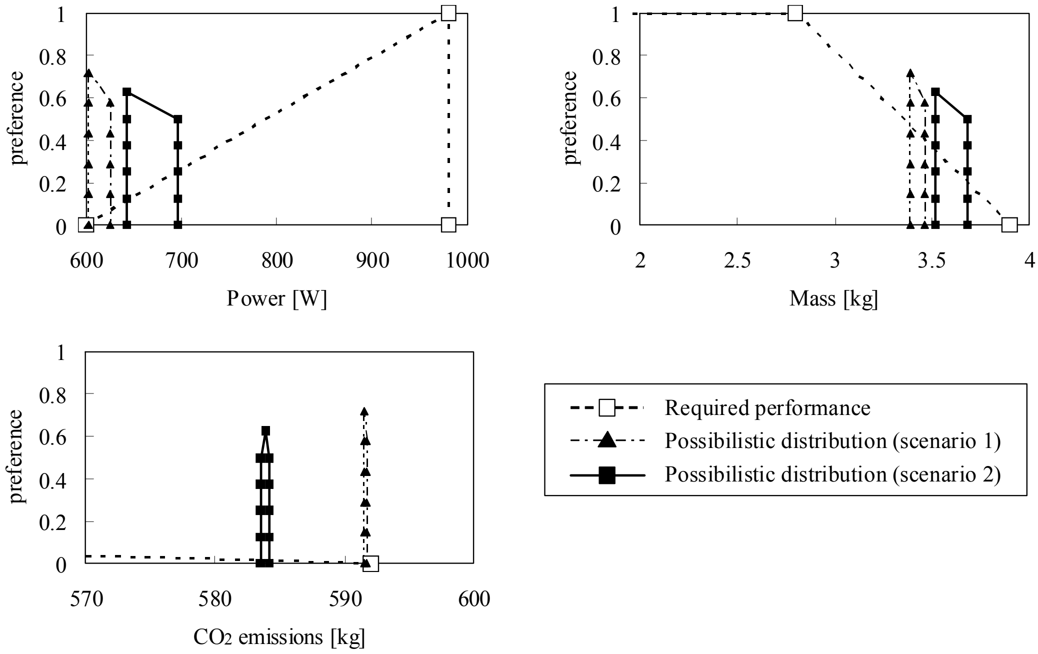


Figure 4. Comparison of possible distributions between scenario 1 and scenario 2

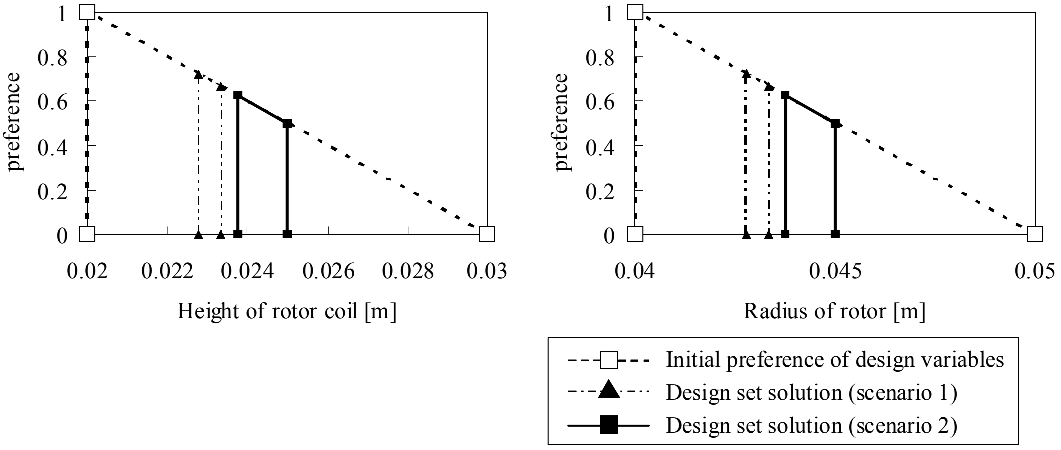


Figure 5. Comparison of design set solutions between scenario 1 and scenario 2

5. Conclusions

As already stated in the introduction, the implementation of the concept of sustainable development requires appropriate methods and tools in product creation processes. This paper indicated the applicability of the PSD approach for obtaining the multi-objective satisfactory solutions not only about technical performances but also about sustainable issues. Therefore, we investigated different officially accepted sustainability indicators and identified which indicators are related to the product development process in a first step. Thereafter, the proposed set-based design method is applied to a multi-objective design problem including technical performances, e.g. power output, and sustainable issues, e.g. CO_2 emissions. Finally, this paper indicated the applicability of our proposal for obtaining the multi-objective satisfactory solutions reflecting the different life cycle scenarios.

However, the approach described clearly shows that the complex relations between decisions in product creation and their effects on the sustainability of products and processes in the product creation process have to be examined in a balanced way. Nevertheless, further research about product-related sustainability indicators must be carried out. Thereby a major challenge is to quantify the social dimension of sustainability. Additionally, the PSD method must be extended by further economical and ecologicals, as well as social aspects. Due to an increasing complexity, the prototypical tool must be developed further. Future research activities have to focus on the development of assistance systems which should be integrated into the working environment of the engineer. What has to be achieved, are products that are economically more successful, ecologically more viable and socially more responsible.

Acknowledgement

This research was supported by the Japan Society for Promotion of Science, Grant-in-Aid for Young Scientists (B) No. 21760109 and Grant-in-Aid for Scientific Research (C), 20560124, in 2009. The authors wish to thank Mr. Martin Ospina and Mr. Simon Kind for their technical assistances. Further research about this topic is supported by the German Research Foundation, DFG PAK 475/1.

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