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Decision-making support for sustainable product creation

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ABSTRACT

A satisfactory multiobjective design that incorporates physical performance as well as sustainability is necessary from a global environmental protection perspective. For obtaining sustainable lifecycles, decision making in the early phases of the design process, considering multiple sources of uncertainty, is important. Previously, we proposed a preference set-based design (PSD) by Inoue et al. (2010) [16] method, which enables a flexible and robust design under various sources of uncertainty while capturing the designer's preference based on his/her knowledge or experience. The present study focuses on a decision-making support for sustainable product creation in the early phases of the design process considering the various design uncertainties. We investigate different officially accepted sustainability indicators and identify the ones that are related to the product development process by considering the physical performance and sustainability of the products concurrently. Thereafter, the proposed method is applied to a multiobjective design problem. This paper discusses the applicability of PSD as a decision-making support method for sustainable development using the design of an alternator as an example.

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 [1]" already in the year 1987. A satisfactory multiobjective design that incorporates both physical performance and sustainability including ecological, economical, and social aspects leads to the sustainable product creation. Since the essential product properties and characteristics are already determined during product development, it is necessary to integrate sustainability into the product development process [2]. The implementation of the sustainable development concept requires the use of appropriate methods and tools in the product creation process. The product properties, which are defined during the product creation process, should support and ensure sustainable development throughout the product lifecycle [3]. For obtaining a sustainable lifecycle, decision making should occur in the early phase of the design process [4]. However, the early phase contains multiple sources of uncertainty in describing the design [5]. Therefore, it is critical to appropriately handle the uncertainties and obtain design solutions reflecting the designer's intension or preferences based on his/her knowledge or experience in the early product creation process. The present study focuses on the decision-making support for sustainable product creation in the early phase of the design process considering the various design uncertainties.

Traditional design practices often regard the engineering design as an iterative process. That is, these practices rapidly develop a "point solution", which they evaluate using multiobjective criteria, and then iteratively move to other points until the process reaches a satisfactory point solution [6]. However, in this iterative process, there is no theoretical guarantee that the process will ever converge and produce an optimal solution. Moreover, using a point solution does not inform us of the uncertainties [7]. A point solution cannot explicitly express the designer's degree of desirability (i.e., preference, intention), which is a type of design knowledge and one of the uncertainty factors, and thus, cannot incorporate the various preference shapes. Thus, the point-based design is a trial-and-error method that uses single values to represent the possible design solutions. Therefore, it is difficult to capture the design creation and reasoning process of designers and to pass on their knowledge to the next generation of designers. Thus, it is important to visualize the design creation and reasoning process of the decision-making support.

In the past, there have been research efforts for incorporating engineering uncertainties into the design process, e.g., including a fuzzy set-based approach [8,9], an interval set-based approach

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[7,10–12], and a probability-based approach [13]. Wood and Antonsson [8] proposed a fuzzy set-based approach, called the imprecision method, for manipulating imprecise design information through the specification of preferences regarding the design and performance variables. This method uses preference functions to represent the designer's desire to use particular values for the design parameters, and employs a fuzzy weighted average algorithm [14] to propagate the uncertainties using engineering equations. However, using a preference function is more expressive than using intervals alone in that preference and possibility can be combined in the calculations. Although the fuzzy weighted average algorithm solves the well-known overestimation problem of conventional decomposed fuzzy mappings [15] using a combinatorial interval analysis, it causes another type of overestimation problem because of the use of the conventional interval arithmetic, which does not consider the causal relations among variables [11,12]. As a result, the imprecision method produces a wider solution than required.

Finch and Ward [11,12] proposed an interval set-based approach that solves the overestimation problem of the conventional interval arithmetic by developing the quantified relations and the interval propagation theorem (IPT). However, this approach cannot explicitly express the designer's degree of desirability (i.e., preference), and thus, only generates bounds on the members of the feasible sets of the design variations.

Probability distributions are often used to describe the variations resulting from stochastic processes. Chen and Yuan [13] proposed a probabilistic approach for achieving design flexibility by allowing the designer to specify a ranged set of design solutions and requirements, and developing a range of design solutions (not single-point solution) that meet the design requirements. However, the approach does not allow the specification of the varying degree of preference of a ranged set of design solutions. In addition, as in most probability-based approaches, the probabilistic representation of the design solutions is limited to a normal curve, and thus cannot incorporate the various preference shapes.

In addition to the individual problems of the aforementioned approaches, there is a common problem in evaluating uncertainties. Even though the methods differ in the types of uncertainties under consideration, as well as their representation and propagation, the common feature is the use of variations (i.e., range or set) in the design solutions and performance requirements, with (or without) expressing the different degrees of the designer's preferences. When the deviations in the design solutions are considered, the resulting performance will correspondingly vary within a range. Therefore, a design metric is required to measure the design preference and robustness of the resulting performance variations with respect to a ranged set of performance requirements.

Previously, we proposed a preference set-based design (PSD) method, which enables a flexible and robust design under various sources of uncertainties while incorporating the designer's preference structure in the early phases of the design process [16]. However, we applied only a structural design problem such as a swing arm structure as a part of a motorcycle considering only the physical performances. This paper focuses on a new decision-making support, based on the PSD method, for satisfactory multiobjective design that incorporates not only physical performances but also sustainability including ecological, economical, and social aspects toward the sustainable product creation. Therefore, we need to investigate the various officially accepted sustainability indicators all over the world. This paper discusses the availability of the PSD method as decision-making support method for sustainable product creation using a case study. The rest of the paper is organized as follows:

(i) Introduction of the PSD method, which has the potential to visualize the design creation and the reasoning process of the decision-making support (Section 2).
(ii) Investigation of the various officially accepted sustainability indicators and identification of the indicators that are both directly and indirectly related to sustainable product creation (Section 3).
(iii) Definition of the calculation method(s) for the multiobjective design problem and obtaining satisfactory multiobjective solutions considering technical performance and sustainability using the design of an alternator as a case study (Section 4).
(iv) Discussion on the availability of the PSD method as a decision-making support method for sustainable production creation (Section 5).

2. Preference set-based design method

The PSD method consists of three steps: set representation, set propagation, and set narrowing, which are described in Ref. [16]. Fig. 1 shows the procedure of the proposed method. The PSD method has the potential to visualize the design creation and reasoning process through the abovementioned steps.

2.1. Set representation: representation of the designer's preference based on his/her knowledge

The representation and manipulation of engineering uncertainties in the early phases of the design process is critical. However, the designer defines his/her preference of the design variables and performance requirements regardless of the various uncertainties. To capture the designer's preference structure on a continuous set, both interval set and the 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, in which any of the PN shapes is allowed to model the designer's preference structure on the basis of his/her knowledge or experience, as shown in Fig. 2, as well as the traditional design specifications (e.g., the larger, the better; the more center, the better; or the smaller, the better). The interval set at the preference level of 0 is an allowable interval, while that at the preference level of 1 is the interval that the designer aims for.

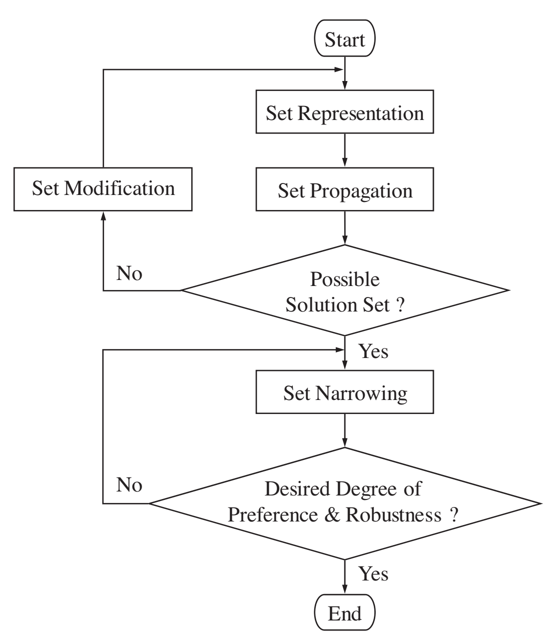

Fig. 1. Procedure of the set-based design method.