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Multi-criteria improvement of complex systems

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ABSTRACT

Designing the way a complex system should evolve to better match customers' requirements provides an interesting class of applications for muticriteria techniques. The models required to support the improvement design of a complex system must include both preference models and system behavioral models. A MAUT model captures decisions related to design preferences, whereas a fuzzy representation is proposed to model relationships between system parameters and the fulfillment of system assessment criteria. The way in which these models are jointly used throughout our entire design procedure highlights that both models must be used in tandem to address managerial and implementation issues involved in an improvement project. The iterative improvement process is supported by a mathematical model, in addition to a software tool that allows our approach to be tested in an industrial case study. The search for adequate parameters regarding the improvement design is supported by a branch and bound algorithm to compute the most relevant actions to be performed. The findings confirm the efficiency of the algorithm.

1. Introduction

To satisfy a fluctuating demand and achieve a high level of quality and service, industries must develop and integrate new features in order to become or remain market leaders [41]. To deal with the complexity of current industrial contexts, new management strategies intended to bring about continuous improvement must take two imperatives into account: complex systems need to be tailored to an evolving context; and improvement assessment proves to be a thorny issue due to its dependence on multiple decisional aspects [4,18]. When designing improvement measures for complex systems, multiple decisions need to be considered [3]. Examples include military information architecture [47] and industrial device performance improvement [5,34]. Such settings increase the multidisciplinary design complexity regarding the fulfillment of functional, technical, environmental, economic and security requirements. In this setting, industries focus more intently on optimization and evaluation activities during the design process in order to improve and adapt complex systems. Reynoso-Meza et al. [48] explains that it is common to state a design problem as an optimization statement, where a specific cost index must be optimized. However, many real world problems require the fulfillment of a set of requirements and specifications. It is not possible to consistently transform heterogeneous factors into one single scale (*e.g.* cost) – this mindset is called *arithmo-morphism* [49]. In that case, all concerns must be taken into consideration explicitly. This is an important issue as some objectives might conflict with others, and a trade-off solution is sought.

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When company designers/operators choose a new architecture to improve their system, they must first ensure that their solutions do not violate any constraints and check whether they satisfy customer needs and technical specifications, as well as the company's strategic goals and interests. Furthermore, these issues are obviously not devoid of budgetary constraints. Two extreme approaches can be adopted. In the first one, as each concern is associated with a different discipline and division within the company, the optimization regarding the different concerns can be sequentially performed after ordering the concerns according to their importance. There is no possible backtrack in this approach: the decisions made at one level (concern) are considered as requirements at the following levels. There may be conflicting requirements among the different concerns. In practice, experience is then used to try to minimize these conflicts and reach acceptable solutions [55].

The second potential extreme approach is concurrent optimization. It involves considering all concerns at the same time (concurrently) rather than considering them one at a time [28,53,38]. Then conflicting requirements, tradeoff relationships among system parameters are taken into consideration in a relevant way. This yields a single global optimization problem where the variables are the system parameter values. However, this global approach is not suited to situations where the mapping from the system parameter values to the fulfillment of strategic goals is not explicitly known, and its evaluation is very costly. Moreover, industries are more inclined to accept continuous improvement of their system rather than a more thorough perturbation of system parameters. The approach proposed in the paper is thus somewhat in-between the standard empiric sequential way (that is often conducted) and concurrent optimization. The empiric sequential approach is used in many industries for the design of complex systems. The outcomes are satisfactory (even-though sub-optimal) as designers and architects take return on past experiences and expertise into account. We propose a sequential approach, but in which backtracking is allowed. We thus propose in this work to proceed by successive improvements from an existing situation. We propose a set of possible actions on the system, where each action modifies the value of one or several system parameters.

In order to bypass the difficulty of the unknown mapping from the parameter values to the fulfillment of strategic goals, the idea is to use a behavioral model based on experience on past designs. The behavioral model of the system helps provide a simple and interpretable approximation of it, which is very useful for both operators and managers [1]. Such a model already exists in different domains: engineering (*e.g.* [29,20,19]), industry design [11], qualitative Bayesian networks [43]. As we are ultimately interested in improvements, we propose a behavioral model that relates the actions to improvements or degradations on the goals. This influence model is provided by experts and expresses their experience [37]. It has been applied to risk management and stock trading [46]. Even if two experts may theoretically come up with two different models, we do not expect large discrepancies at this stage. Apart from the influence model, two other inputs are also necessary to relate the actions to the overall impact on the satisfaction of the system. The first one synthesizes the results of the influence model. Assume that two actions are performed, the first one improves a goal and the second one is detrimental to the same goal. Then what is the overall impact on the goal? This depends on the attitude of the decision maker regarding the risk [44]. The first input describes this attitude. The second input weighs up goals and produces an overall satisfaction of the system. It is based on a multi-criteria model to aggregate the goals [52,24,25]. These two inputs are subjective and represent the decision maker's preferences.

In order to identify the set of actions that allows the decision maker to improve the overall satisfaction of the system in the most efficient way, we propose to separately deal with the multi-criteria model and the influence model (and its synthesis). The reason for this separation is that only a behavioral model of the influence of the system parameters on the fulfillment of strategic goals is known. First (at the strategic level) we start by identifying the goals for which it would be more rewarding to improve the system. Then (at the operational level) we aim at finding, through a branch-and-bound algorithm, the set of actions that would improve these goals as much as possible at the minimum cost. Although two steps are considered, backtracking is allowed when there is no set of actions that could improve the goals identified in the first step. In this case, the first step generates other goals to be improved and the optimization algorithm is launched once more.

This paper is organized as follows. Section 2 outlines a formal model for the problem of interest here. It begins by modeling the search for outputs to be improved as a multi-criteria optimization problem, before integrating this proposal into an iterative system improvement procedure. A general algorithm, based on two functions (FindCoalitions and FindActions) is proposed. Section 3 then describes function FindCoalitions: it identifies the coalition of goals/criteria to be improved first. Section 4 describes the influence model and the subjective model to synthesize its results. A branch-and-bound algorithm (function FindActions) is implemented in Section 5 as an efficient solution step. The numerical efficiency of function FindActions is analyzed in Section 6. Section 7 proposes a case study inspired from the adaptive management of a manufacturing plant. Section 8 discusses some works related to improving the competing architectures available in a multidimensional assessment context. Finally, a nomenclature of the main definitions and notations is given in Appendix A.

2. Description of the optimization algorithm

2.1. List of concepts

For starters, a complex system is characterized by input *parameters* $\gamma_1, \ldots, \gamma_p$, *e.g.* the accurate definition of all entities in a military force and its ties, or industrial device control parameters. The set of all possible parameter vector values of $(\gamma_1, \ldots, \gamma_p)$ is denoted by: $\Gamma = \Gamma_1 \times \cdots \times \Gamma_p$. A *system* is thus defined by an element $\gamma \in \Gamma$. Not all elements of Γ lead to