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Multi-disciplinary and multi-objective optimization problem re-formulation in computational design exploration: A case of conceptual sports building design

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A R T I C L E I N F O

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A B S T R A C T

The benefits of applying multi-objective optimization (MOO) in building design have been increasingly recognized in recent decades. The existing or traditional computational design optimization (CDO) approaches mostly focus on optimization problem solving (OPS), as they often conduct optimizations directly by assuming the optimization problems in question are good enough. In contrast, the computational design exploration (CDE) approaches defined in this research mainly focus on optimization problem formulation (OPF), which are considered more essential and aim to achieve or ensure appropriate optimization problems before conducting optimizations. However, the application of the CDE is very limited especially in conceptual architectural design. The necessity of re-formulating original optimization problems and its potential impacts on optimization results are often overlooked or not emphasized enough.

This paper proposes a new CDE approach that highlights the knowledge-supported re-formulation of a changeable initial optimization problem. It improves upon the traditional CDO approach by introducing a changeable initial OPF and inserting a CDE module. The changeable initial OPF allows expanding the dimensionality of an objective space and design space being investigated, and the CDE module can re-formulate the changeable optimization problem using the information and knowledge extracted from statistical analyses. To facilitate designers in achieving the proposed approach, an improved computational platform is used which combines parametric modeling software (including simulation plug-ins) and design optimization software. Assisted by the platform, the proposed approach is applied to the conceptual design of an indoor sports building that considers multi-disciplinary performance criteria (including architecture-, climate- and structure-related criteria) and a wide range of geometric variations. Through the case study, this paper demonstrates the use of the proposed approach, verifies its benefits over the traditional method, and unveils the factors that may affect the behaviour of the proposed approach. Besides, it also shows the suitability of the computational platform used.

1. Introduction

Nowadays, multi-objective optimization (MOO), coupled with building performance simulation and parametric modeling, has been increasingly used to improve overall building performance [1–4]. However, the importance of optimization problem formulation (OPF) or re-formulation is often overlooked in conceptual architectural design. Most existing studies are only interested in optimization problem solving (OPS), i.e. running various algorithms to search for optimal solutions based on already formulated or initially formulated optimization problems, without sufficiently demonstrating how the problems are formulated and how they may affect the optimal results.

It is through the OPF that a design task can be partially converted to an optimization problem. Key components of the OPF include at least two aspects: (1) the formulation of objective space - selecting objective and constraint variables (i.e. output variables) and constraint values; (2) the formulation of design space - selecting design variables (i.e. input variables) and their domains. The former determines all performance goals and constraints to be achieved; while, the latter determines all possible design alternatives that can be searched from.

In fact, the OPF is more essential than the OPS. If an optimization problem is formulated in meaningless way, it makes no sense to solve it. An improperly formulated objective space may lead to entirely wrong results; and, an improperly formulated design space may provide a poor

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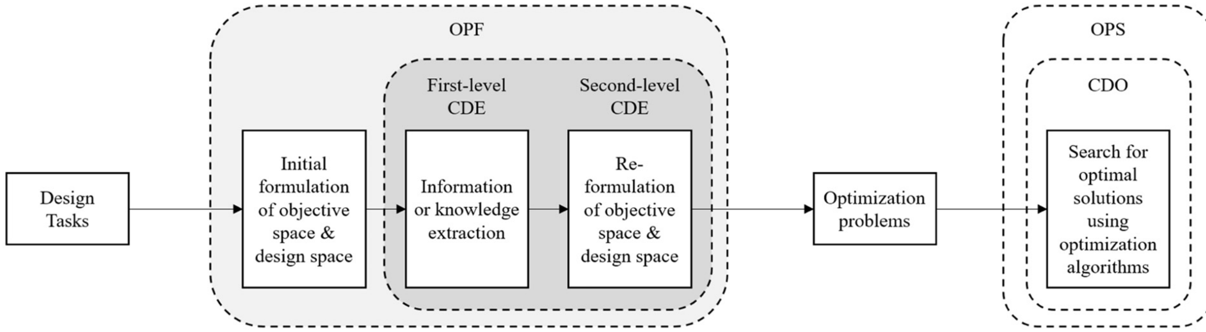

Fig. 1. The relationships between the CDO, CDE, OPS and OPF.

“design alternative pool” to search from. Apparently, it is not wise for designers to dive directly into the OPS, without properly considering the OPF. This is especially true for conceptual architectural design optimization. During the OPF, designers usually have large freedom in defining the objective space and design space, which may lead to improper definitions. The initial OPF is often unstable and poorly defined, due to the “ill-structured” nature of design tasks and the limited knowledge support (see Section 2). Thus, it indicates the need of re-formulating or revising the initial OPF with more sufficient information and knowledge support, which we consider as computational design exploration (CDE), a crucial step prior to computational design optimization (CDO).

Specifically, we define the CDE as the process of extracting useful information or knowledge (i.e. first-level CDE), and of applying it to re-formulate the original optimization problem (i.e. second-level CDE). The aim of the CDE is to achieve a good OPF before diving into the OPS. In contrast, the CDO is defined as the process that is only keen on the OPS. The aim of the CDO is to search for optimal solutions for a given or fixed optimization problem. The relationships between the CDO, CDE, OPS and OPF are summarized in a diagram (Fig. 1).

In response to the need of knowledge-supported re-formulation, this paper proposes a new holistic approach, emphasizing the CDE in which relevant information and knowledge are extracted to support the re-formulation of the initial optimization problem in a more informed manner. Statistical analysis techniques, such as correlation analysis, cluster analysis and sensitivity analysis are used for the knowledge extraction. An improved computational platform is also used for achieving the proposed approach, which integrates parametric modeling software (including simulation plug-ins) and design optimization software. With a focus on the conceptual design of indoor sports buildings, the proposed approach is applied to a complex real-world project which considers multi-disciplinary performance criteria (including architecture-, climate- and structure-related criteria) and a wide range of geometric variations. Through the case study, this paper demonstrates the use of the proposed approach, verifies its benefits over the traditional method, and unveils the factors that may affect the behaviour of the proposed approach. Besides, it also shows the suitability of the computational platform used.

2. Optimization problem (re)formulation and knowledge support

2.1. Initial formulation of an optimization problem

Due to the “ill-structured” nature of design tasks, the initial formulation of an optimization problem is usually unstable. As first defined by Simon [5], a building design task is ill-structured (i.e. lack of definition) in a number of respects; and, it seemed to reach a consensus, among researches in the late 1990s, that most of real-world tasks, in particular design tasks, are ill-structured [6–16]. This is especially true in the conceptual design stage. In this stage, there are no definitive goals and constraints, since the goals are usually vague and many performance criteria maybe unknown; and there are no definitive solutions either, because a wide range of different solutions can be valid responses to the goals and constraints [17]. Thus, the initially formulated objective space and design space are usually unstable; they are subject to change (i.e. re-formulation) once more information and knowledge becomes available.

Due to the limited knowledge support, the initial formulation of an optimization problem is often poorly defined. At the very beginning of a conceptual design, the designers are usually not able to perceive every aspect of the design task, since they have to rely on their limited knowledge (e.g. educated guesses and/or intuition). For converting the design task to an optimization problem, they have to answer: what are the most important design issues and performance criteria; and what kinds of solutions most probably manage to solve these issues? According to Logan and Smithers [9], the designers' answers to these questions are often subjective and highly context dependent; not surprisingly, the initial expression of the design task is often misleading. From the perspective of the OPF, the initial objective space and design space are probably poorly defined.

2.2. Re-formulation of an optimization problem

Given the limitations above, the re-formulation of the initial optimization problem is inevitable in conceptual architectural design. It requires a balance between reducing computational cost and increasing design creativity, i.e., between variable screening and variable adding. Here, design variable screening refers to the process of screening out unimportant design variables (that contribute the least to the variation of objective variables), and design variable adding refers to the process of introducing new design variables (that create new design variations). Objective variable screening refers to the process of identifying the most meaningful performance criteria to be considered as final objectives, and objective variable adding refers to the process of introducing new objective variables.

This balance is challenging due to its conflicting nature; designers may struggle between reducing and increasing the dimensionality of a design space and of an objective space. Specifically, for the re-formulation of a design space, the decision whether or not to include more design variables has to be made. From the perspective of increasing design creativity, the incorporation of new design variables is crucial for the creative design [18]; while from the perspective of reducing computational cost, the best model is usually the simplest one [19], and entities should not be multiplied beyond necessity according to the principle of “Occam's razor” [20]. Similarly, for the re-formulation of an objective space, the decision whether or not to include more objective variables has to be made. The incorporation of new objective variables may be beneficial for a more holistic assessment, while it also means the increase of computational cost. In this regard, the total number of final objective variables is often limited to less than or equal to three, given the challenges of handling many-objective optimization problems [21].