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Toolbox for super-structured and super-structure free multi-disciplinary building spatial design optimisation

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ABSTRACT

Multi-disciplinary optimisation of building spatial designs is characterised by large solution spaces. Here two approaches are introduced, one being super-structured and the other super-structure free. Both are different in nature and perform differently for large solution spaces and each requires its own representation of a building spatial design, which are also presented here. A method to combine the two approaches is proposed, because the two are prospected to supplement each other. Accordingly a toolbox is presented, which can evaluate the structural and thermal performances of a building spatial design to provide a user with the means to define optimisation procedures. A demonstration of the toolbox is given where the toolbox has been used for an elementary implementation of a simulation of co-evolutionary design processes. The optimisation approaches and the toolbox that are presented in this paper will be used in future efforts for research into- and development of optimisation methods for multi-disciplinary building spatial design optimisation.

1. Introduction

Many engineers in the built environment experience optimisation as a challenging task. This is because it is usually a time consuming trial-and-error procedure, in which knowledge and experience are first needed to create designs, that in turn need to be assessed and possibly modified. Many research projects involve the development of optimisation methods to create and analyse designs to aid engineers. These developments concern advanced optimisation methods, often specialised to small sub problems (for a single discipline) in the design process. Such a specialisation exists because building spatial design problems are too large for a single design tool. Engineers are therefore invaluable to the design process since their experience can reduce a design problem drastically. However, it cannot be expected that an individual engineer oversees the complete design problem, and thus complex relationships between the disciplines might go unnoticed, leading to suboptimal designs. For this, multi-disciplinary building optimisation could be supportive, but it needs a method to handle the large design search spaces involved. This paper aims at the development of such a method by means of a toolbox that is presented here and asks the question of how to represent design search spaces such that optimisation methods find efficient solutions. This paper is an extension of [1], in addition to the contribution in [1] (a consideration and proposition for building spatial design optimisation) this paper discusses: a toolbox for building spatial design optimisation; and a toolbox demonstration.

Prior to reading this paper it is important to understand the terminology concerning optimisation and data structures in optimisation. Optimisation aims to minimise or maximise an objective value by the variation of design variables, while at the same time satisfying certain constraints. What is important for optimisation is the representation of the design search space, which is the selection of design variables that are used to parametrise the solutions for the problem (design variables not part of the selection are constant or depend on the representation itself). The representation affects the possibilities and performance of the optimisation methods, e.g. a complex dynamic data structure might be too difficult to handle by most types of optimisation methods. In this paper, terminology will be used as found for optimal process synthesis in chemical engineering, where super-structure representations are distinguished from super-structure free representations [2]. In a super-structure, the design search space has a fixed number of design variables, meaning all design alternatives are pre-encoded, which makes for

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a static data structure. This enables the search for an optimum in a systematic manner by using classical parameter-based optimisation methods. Super-structure free optimisation uses a design search space in which new design variables may originate or disappear, which can be seen as a dynamic data structure. Such a design search space allows for discovering unexpected new alternatives that were not pre-encoded. Typically, super-structures allow for formulating optimisation problems in the language of mathematical programming (using equations and inequalities). Free representations are formulated differently, for instance by describing initialisation procedures and variation operators that form the design search space. The difference between super-structure versus super-structure free approaches is a recurrent theme in specific fields of optimisation [2], whereas this topic has hardly been addressed for building design.

The design search space used in this paper entails the layout and dimensioning of building spaces, i.e. the building spatial design. For this design search space, a super-structure and a super-structure free approach have been developed and compared. Moreover, a method to carry out transformations between the two representations will be discussed, which is envisioned to enable both approaches to efficiently cooperate on a large design space. Finally a toolbox is presented, which is created to develop and investigate different methods of building spatial design optimisation.

2. Related work

In the literature, research on building optimisation can be found that takes into account objectives concerning energy consumption, as is carried out in [3,4]; structural design in [5–7]; construction costs in [8]; and thermal building design [9,10]. Also, optimisation is thoughtfully combined with Building Information Modelling [11–13]. Different energy performance criteria are combined in [14,15].

A commonly used optimisation method is evolutionary optimisation, where design variables are stored in a so called genome that can be modified by means of mutation and recombination operators. Other optimisation methods are applied as well, like gradient-based optimisation for topology optimisation in [16], or the analytical derivation of optimal truss layouts in [17]. The use of optimisation methods for building performance optimisation is however still not widespread and many issues need to be solved. One difficulty is to allow for more degrees of freedom in the optimisation. This is addressed in this paper by defining design search space representations that allow for variations of the (global) building spatial design.

The super-structure terminology finds its origins in the process industry, where the optimal configurations of chemical engineering plants are sought. For example, Jackson [18] described the structure of flow configurations of chemical reactors with a super-structure, although without explicitly mentioning the term. Various recent works [19–21] use the terminology for other engineering fields too. A super-structure prescribes the possible design alternatives to be considered in optimisation, which results in a selection of alternatives. This limited and fixed number of alternatives improves the chance of finding the global optimum. A super-structure enables an optimisation problem to be solved by mathematical programming, for which standard solvers exist (e.g. [22]).

Super-structure free optimisation has been suggested to overcome the limitations of super-structures for designing chemical process configurations. Emmerich et al. [23] propose to use replacement, insertion, and deletion rules to modify (mutate, recombine) designs in evolutionary algorithms. However, the development of these local modification operators requires domain knowledge. Voll et al. [2] suggest a more general framework that uses generic replacement rules in evolutionary algorithms. A similar strategy is followed in [24], where it is exemplified for the optimisation of decision diagrams. Other examples of super-structure free design spaces include the work found in [6,25]. There are only a few optimisation methods that can handle super-structure free representations, namely simulated annealing, evolutionary algorithms, and heuristic local searches. Simulated annealing has been used in the design of processes, e.g. in [26]. In the field of structural design, [27] describes a super-structure free approach in the optimisation of structural topologies. Moreover, in [28] simulations of a co-evolutionary design process (these simulations can also be interpreted as asymmetric subspace optimisation [29]) are used to find a building spatial design for which a structural design created by certain design rules shows minimal strain energy.

3. Building optimisation representations

A building spatial design representation determines—to a large extent—the design space of the building spatial design problem. Designs can be constrained by how they are represented e.g. a representation that is restricted to orthogonal shapes cannot represent curves in a building design. Optimisation efficiency and success is dependent on the solution space (i.e. design space), therefore it is important to consider the used representation for building design optimisation. In this section two representations are suggested, the supercube representation and the movable and sizeable representation, which are based on the super-structured and the super-structure free approaches respectively.

3.1. Super-structure based representation

Design search space. A supercube (SC) is introduced to describe a building spatial design B by means of a super-structure design search space representation. A supercube consisting of cells is described by four vectors: **w**, **d**, **h**, **b**. Eq. (1) shows the variables used. Here **b** describes the existence of the cell with indices i, j and k in space ℓ, where $b^{\ell}_{i,j,k}$ with a value "1" means the cell i, j, k is active and describes a part of space ℓ while "0" means the cell is inactive. A space ℓ can thus be constructed out of the supercube cells that are activated for that space. Finally, w_i, d_j and h_k describe the continuous dimensioning of the supercube's cells. The entire supercube is used to perform design modification, therefore the complete design space is described by the vectors **w**, **d**, **h** and **b**. Fig. 1 shows the supercube notation for an example

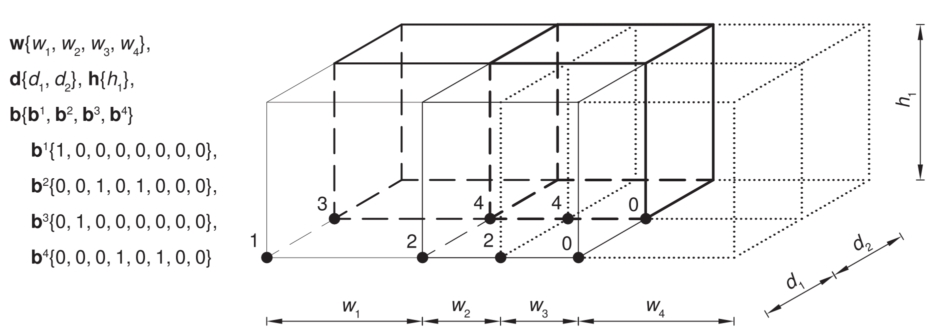

Fig. 1. Supercube representation of a building spatial design, space 2 and 4 are described by two cells each, the two right cells are not used to describe a room.