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Automated design studies: Topology versus One-Step Evolutionary Structural Optimisation

H. Hofmeyer *, J.M. Davila Delgado

Eindhoven University of Technology, Department of the Built Environment, The Netherlands

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ABSTRACT

This paper presents the development of a virtual toolbox for the study of spatial–structural design processes. It will be able to transform a spatial design into a structural design. After structural optimisation, the structural design is interpreted as a spatial design. This spatial design is then modified to comply with the initial design requirements after which a new cycle starts. The transformation and optimisation processes within the toolbox can be altered, allowing automated design studies to be carried out. In this article, two processes for the structural optimisation are investigated to determine which is most suitable for specific conditions. These two processes are: (a) Topology Optimisation applied to complete structural systems for buildings; (b) Evolutionary Structural Optimisation for which only the first step is used. It can be concluded that: (a) although Topology Optimisation is formally more correct, One-Step Evolutionary Structural Optimisation will yield almost the same qualitative results, (b) quantitatively the methods cannot be compared exactly, however, it is likely that Topology Optimisation results in more efficient structures and (c) Topology Optimisation always leads to stable structures, whereas One-Step Evolutionary Structural Optimisation may yield a singular stiffness matrix, although this has no influence on the spatial design derived from the optimised structural design. It is intended to utilise the optimisation techniques in the virtual toolbox leading to design studies and to transcend additional transformation and optimisation processes in the virtual tool box via formal description. Fields of application are the academic study of spatial–structural design processes (i.e. design theory), the optimisation of all possible structural design types (i.e. design optimisation), and the generation of design instances (i.e. generative design).

1. Introduction

Engineers in the field of Architecture, Engineering, and Construction (AEC) are used to regard achieved design solutions as products of a creative process, i.e. not by working from a single problem towards a single solution, but by an exploration of problems and solutions simultaneously [1]. As such, it is generally acknowledged that there is a need for dedicated tools that support the designer to explore a solution space and evaluate the outcome of the design process [2–10]. For example, Austin et al. presented a matrix which enables scheduling a building design process [2], Camelo and Mulet suggested a method to support the design process [3] and Chou et al. published a procedure to evaluate the performance of the design project [4]. Eilouti presents models to capture implicit knowledge from previous (architectural) designs in order to use them explicitly in future designs [5]. On a system level, Isikdag and Underwood present two templates to enable data models in AEC processes to support synchronous interaction between designers during the entire lifecycle of the building [6]. Also, practical but not less advanced developments are available from research by Krish that concerns the generation of creative designs based on a parametric template and the automatic evaluation of these designs, all within the workflow of the designer [7]. Related to evaluation, Nelson et al. studied the possible improvement of measurement types during the generation of ideas (e.g. designs) [8]. Finally, Rafiq et al. [9] and Zang and Wang [10] presented two approaches (evolutionary and parallel evolutionary), which are analogous to the work by Krish, for the creation of design concepts.

Furthermore, much fundamental research on AEC design is being carried out: relationships between domain specific design instances (e.g. a spatial design and a structural design) are subject to investigations. Also, the creative, primarily design process is studied because understanding the way designers influence the design processes and the behaviour of their colleagues, may lead to improvements in the design processes and their products. Several research projects have been carried out to investigate the multi-disciplinary character of the AEC field and to develop

* Corresponding author.
E-mail address: h.hofmeyer@tue.nl (H. Hofmeyer).

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computer aided tools to support the design processes, e.g. [11–14]. Some other related research projects are described below.

In descriptive research data models are developed that formalise data and their relationships regarding specific aspects of the design process. Related to this study, relevant data models have been specifically developed for spatial design [15–17], for structural design [18], and for the relation between spatial and structural design. For the latter group, Martini and Powell showed that the top-down representation of engineering drawings may be better than a bottom-up computer representation [19]. With the aim to develop integrated design systems, Sause et al. presented an object-oriented approach to unify structural product and process models [20]. Making use of that object-oriented approach, Nguyen and Ha developed a concept for a data model for architectural design, structural design, and code compliance checking. For the last two aspects, a prototype program was also developed [21]. In addition, Khemlani et al. developed an approach using a general applicable product database and a project specific database. However, during this development, their most important achievement was the proposal of an explicit formulation of the "space-structure dilemma" and a possible solution for this using an existing so-called "split-edge data structure" concept [22]. Similar propositions for a data model including structural and spatial information are shown in the work by Matthews et al. [23]. Eastman and Jeng realised that the evolution of data models may require a specific data model set-up and demonstrated this by a spatial, structural, and physical view of a building design example [24]. Then Rivard and Fenves suggested a data model that incorporates both an object-oriented data model and two design evolutionary capable abstraction levels for multiple views, again illustrated by a spatial–structural example [25]. Scherer and Gehre use a less complex method but implemented the data model in a primarily design assistant system prototype [26]. Mora et al. worked out a very detailed data model, explicitly for spatial and structural design aspects [27], which was loosely based on the work by Rivard and Fenves as mentioned above [25]. This finally led to an advanced design system prototype in 2008 by the same authors [28]. Assuring that data models are suitable for multiple representations and design evolution remains an interesting issue and can also be solved via rather different strategies [29].

Additional research has yielded programs, procedures, and concepts for generating (or measuring [30]) spatial and structural design solutions. The oldest but still active domain in this area of research is that of automated facilities layout that transforms design requirements into a spatial design [31,32]. Also, so-called shape grammars (or other techniques) can be used to generate spatial designs [33,34] by starting with an initial design and manipulating it by grammatical rules that modify the basic elements of the design. For structural design, a distinction should be made between two types of research. Studies of the first type are aimed at the optimisation of an existing structural design by means of expert systems, form-finding, or Topology Optimisation [35–47]. An example is given in a paper by Sigmund, in which a beam with a given geometry, load and constraints, is optimised by assigning more or less mass to certain areas of the geometry [35]. In the second type of research the actual one-way transformation and evaluation of a spatial into a structural design are investigated [48–54]. Work by Huang et al. [51] may be taken as an example here, where a concept is developed to automatically generate structure models for estimating the sustainability performance of volumetric architectural designs at an early stage. For the second type of research, the technique of grammars (e.g. shape annealing) could be used as well [54].

The complexity of the design process, due to the often parallel evolution of the design instance and the design requirements requires dedicated design support tools [1]. However, most research projects in the two areas of research mentioned above, assume fixed design requirements and design instance evolution only. Besides, from a domain specific view, the basic underlying idea used is that in the design process a more or less one-way path runs from a spatial to a structural design. A third field of research is focussed on the provision of support to multidisciplinary design processes through an approach that assumes a strong interaction between the various disciplines involved in the design process [55]. Following this concept, the idea of a virtual toolbox has been proposed, which develops and modifies a spatial–structural system through multiple cycles [56–58], Fig. 1.

A single virtual toolbox cycle n consists of four transformations (each to be selected from several possibilities) as shown in Fig. 1 on the right: (1) a transformation of a spatial design $2n-1$ to a structural design $2n-1$; (2) the optimisation of the structural design; (3) the transformation of the optimised structural design $2n$ into a spatial design $2n$ and (4) adjusting the spatial design to (partly) comply with the initial design requirements, which leads to spatial design $2n-1$, with n increased by 1. Usually, several cycles will be carried out, thus with spatial design $2n-1$ being used as input for the next cycle, with n increased by 1, with all cycles together forming a single "run" of the virtual toolbox.

The goals, functions, and applications of the virtual toolbox can be interpreted in several ways [57] and thus it is important to avoid over-simplified conclusions. In this article, the virtual tool box is regarded as providing support in two different ways.

First, it supports the designer to explore a solution space and evaluate the design process outcomes, as discussed at the start of this section. Technically, the working of the virtual toolbox can then be seen as co-evolutionary optimisation [1], where the spatial designs are equivalent to design requirements and the structural designs are equivalent to design solutions, i.e. in co-evolutionary optimisation, design requirements and design solutions both change and influence each other during design iterations. In this exploration of a solution space, it is likely that transformation methods and their settings should be able to be changed by user-intervention during the cycles or run, i.e. the user may think that a different transformation method is now more appropriate for a specific design instance. Few support tools exist to explore a spatial–structural solution in some co-evolutionary way as proposed here by using the virtual toolbox.

Secondly, the transformation or modification processes can be varied for different runs of the tool box and the resulting spatial and structural design evolution can be studied by means of the "Measure" in the right part of Fig. 1. Also, using the same strategy, the influence of selected transformation processes on the behaviour of sub-sequential transformations (via the design measures) can be studied as well. Because now user-intervention does not take place during the run, the behaviour of the run could be similar to the behaviour of solutions of non-linear differential equations, i.e. the behaviour could show limit cycles, multiple equilibrium states, bifurcations, etc. If these phenomena will occur, they will not be seen as a problem, but simply as part of the behaviour of a design process. If the virtual tool box is used for the studies mentioned here for the last case, it is important to note that this is not on supporting the design process, but on studying the design process and the fundamental relationship between spatial and structural design, more related to the domain of design theory. As such the virtual toolbox could also be regarded as a cognitive model of design, something that is also an additional function of the co-evolutionary approach [1]. In this article, these studies are referred to as "automated design studies". As far as known to the authors, only few publications exist on automated design studies related to spatial and structural design [48–54].

The contribution of this paper is that two methods for the structural optimisation process of the virtual toolbox have been applied to decide which process is applicable under which conditions. These two processes are: (a) Topology Optimisation (TO), for which