CO-EVOLUTIONARY SPATIAL-STRUCTURAL BUILDING DESIGN OPTIMISATION INCLUDING FACADE OPENINGS

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Abstract. Within co-evolutionary building design simulations, a spatial design can be automatically transformed into a structural design, and its structural performance can lead to modifications of the spatial design, after which a new cycle starts. This paper presents two procedures to include facade openings in these simulations, to allow for future simulations that include lighting. The first procedure reassigns a fixed pattern of facade openings to the spatial design each cycle, whereas the second procedure only assigns a pattern at the start, and modified spaces inherit their openings. For structural peformance, it is concluded that deterministic vertical opening patterns, with a low facade opening ratio, lead to a reduction of the number of stories, and consequently optimise the structural design. Also, it is shown that the first procedure maintains facade opening ratios during simulations, whereas the second procedure leads to decreasing openness, and more unconnected spaces. As such the first procedure is considered for an upcoming project, where spatial-structural-thermal-lighting building optimisation is investigated, including non-rectangular spatial designs.

Keywords. Spatial-Structural Optimisation; Co-evolutionary Design; Structural Design; Facade Openings.

1. Introduction

State-of-the-art design support tools, if used for multi-disciplinary building optimisation, often start with a fixed Building Spatial Design (BSD), which includes building spaces and their locations. However, a predefined BSD may exclude optimal (domain specific) solutions, and it can be shown that allowing a BSD to be modified during discipline related optimisation will allow for better performing designs (Boonstra et al, 2018). A suitable approach to obtain BSD modification is the application of co-evolutionary design (Maher, 2000), which iteratively explores both a problem and solution space. Co-evolutionary design has been implemented for design support and optimisation of BSDs and their

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structural and thermal designs (Boonstra et al, 2018). However, although the structural designs may involve (implicit) openings, so far facade openings have not been considered explicitly. But for future research, including functionality and lighting, openings must be taken into account. Here, two procedures will be introduced to include and manage facade openings in co-evolutionary building design simulations. The first procedure (re)assigns a fixed pattern of facade openings to the spatial design each cycle, whereas the second procedure only assigns a pattern at the start, and modified spaces inherit their openings. Then, a case study investigates these procedures for an application of co-evolutionary building design simulation to spatial-structural optimisation.

2. Related research

In the field of Architecture, Engineering and Construction (AEC), it shows to be very time-consuming to design even a single BSD in the conceptual design phase (Flager et al, 2009). This aspect has a significant effect on the quality of the final building, for all subsequent design phases rely strongly on the conceptual design decisions, and major redesign efforts cannot be made later in the process (Okudan and Tauhid, 2008).

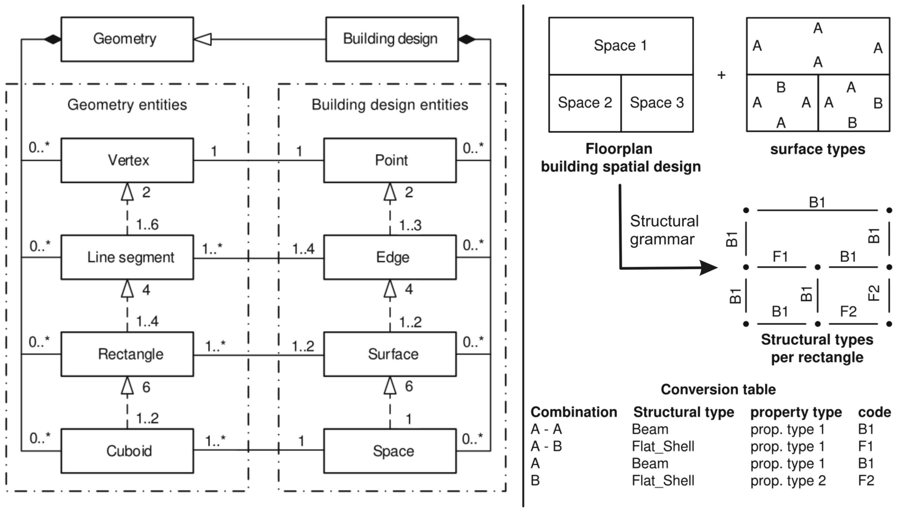
Single Disciplinary Optimisation (SDO) can support (conceptual) design, by finding better solutions with respect to e.g. energy consumption or structural design (Fuyama, Law and Krawinkler, 1997). However, the time-consuming search for trade-offs between the disciplines still has to be made (Machairas, Tsangrassoulis and Axarli, 2014). Multi-Disciplinary Optimisation (MDO) provides a solution, by optimising either a weighted sum of the objectives (e.g. Chantrelle et al, 2011), or conceiving a so-called Pareto Front Approximation (PFA). The latter offers a ranking of design alternatives (only), e.g. for the structural and daylight optimization of classrooms (Flager et al, 2009). Another well known type of optimisation is the use of genetic algorithms (Evins, 2013; Beume, Naujoks and Emmerich, 2007). Heuristic algorithms use intuitive judgement to find design solutions, and although their functioning can be difficult to track (Verhagen et al, 2012), optimal solutions may be found (Evins, 2013). Heuristic algorithms can explore design search spaces during conceptual spatial design (Stiny, 1980) and structural design (Geyer, 2008). Most of the aforementioned approaches, except co-evolutionary design (Maher, 2000) use a predefined design search space, thus limiting the creativity and reach of the design solutions.

A so-called BSO Toolbox has been developed to study the optimisation of BSDs and their discipline designs (Boonstra et al, 2018): An initial BSD is extended with domain specific designs (e.g. a structural and a thermal design); these designs are evaluated; and the BSD is modified. How this approach relates to e.g. a multi-fitness solver, using evolutionary algorithms, is shown in Boonstra et al (2021).

3. Methodology

3.1. BSO TOOLBOX

The BSO Toolbox is an open source C++ library for BSD design and optimisation (Boonstra and Hofmeyer, 2020). The BSD is represented by the “Building design”, shown in figure 1 on the left, which consists of spaces, these spaces made by surfaces, in turn consisting of edges and points.



Conversion table

Combination	Structural type	property type	code
A - A	Beam	prop. type 1	B1
A - B	Flat_Shell	prop. type 1	F1
A	Beam	prop. type 1	B1
B	Flat_Shell	prop. type 2	F2

Figure 1. On the left UML of ConFormal (CF) representation, on the right a structural grammar.

Another used representation is the ConFormal (CF) model, shown in figure 1 by “Geometry”. At the geometry level, cuboids are formulated, which are made of rectangles, line segments, and vertices. By a process defined as conformation, these cuboids are generated such that they can be seen as building blocks for the spaces, with their vertices not intersecting any line segments, rectangles or cuboids. For the CF model, so-called design grammars are defined that generate domain-specific models for the evaluation of domain-related objectives. Relevant in this paper are the structural grammars that generate a structural design consisting of (1) structural components, (2) loads, and (3) constraints. Practically, the structural grammar works as shown in figure 1 on the right. The BSD has spaces, for which the surfaces may have been assigned with surface types. The structural grammar follows the conversion table (on the bottom right of figure 1) and generates structural types and properties (e.g. the Young’s Modulus) for the rectangles corresponding to the surfaces. Hereafter, each rectangle is provided with structural components (trusses, beams, or flat-shells) as a function of the structural type (Boonstra et al, 2018).

In Boonstra et al (2018) the BSO Toolbox is used for the spatial-structural optimisation of BSDs, where BSD modification is carried out by Scale & Subdivide: After adding to the BSD a structural design, for each structural component the strain energy [Nmm] is determined. Then a selected number of spaces that contain the structural components with the lowest strain energy are deleted, and these spaces are brought back into the design by splitting the spaces with the highest strain energy in half across their longest side (width or depth). Lastly, the BSD is scaled horizontally such that the original volume is restored. Here, this type of optimisation will be used for the demonstration of facade openings.

3.2. FACADE OPENINGS

To introduce facade openings, the BSO Toolbox has been extended by an additional property for the rectangles in figure 1, namely the face type, which can be "open" or "closed". Also layers of rectangles have been introduced. For a BSD a single set of horizontal layers is generated, in which each layer consists of all rectangles with the same height position of their centre point. For vertical layers, four sets of layers are made, one set for each direction (north, east, south, west), as shown in figure 2 at the bottom right. For instance, each of the six layers (x = 1 to 6) within the north set contains all facade rectangles that face north, with the same position of their centre point in east-west direction. Six facade opening patterns have been tried, as shown in figure 2 at the top left. Deterministic Horizontal (DH) defines the face type of rectangles in a certain horizontal layer (all around the building) all "open" or "closed", based on the facade opening ratio [0 to 1], which is the number of open layers over the total number of layers. As can be seen in figure 2 at the top right, for the same opening ratio this offers several possibilities if the first position of the pattern and the number of equal layers (open or closed) is varied: All possibilities will be used in the parameter study in section 4. Deterministic Vertical (DV) and Diagonal (DD) function in a similar fashion. Stochastic Horizontal (SH) and Vertical (SV) still assign "open" or "closed" to all rectangles of a layer, but whether a specific layer is "open" or "closed" is determined randomly, however, still assuring the opening ratio. Finally, Stochastic Rectangle (SR) randomly assigns "open" or "closed" to the rectangles, but again keeping track of the opening ratio, now defined as the number of open rectangles over the total number of (facade) rectangles. Finally, note that the opening ratio applies to each set of layers (so horizontal, north, east, south, west) separately. See for more details De Goede (2019).

3.3. LOAD PANEL

In section 3.1 it was explained that the structural grammars provide each rectangle with structural components. In this paper, for rectangles with face type "closed" a flat-shell component is generated. For rectangles that are "open", no structural components should be generated, for in practice the "open" rectangles will contain a transparent facade system, which does not contribute to the structural performance of the building. However, the facade transfers wind loads to the structure. Therefore, still a flat-shell structural component is added to the "open" rectangles, but now having a very low stiffness, and is consequently defined as a "load panel". In a validation study it was found that if the load panel's Young's Modulus is multiplied by 1E-5 compared to the normal flat-shells, wind loads are transferred correctly, while the contribution to the building's structural behaviour is negligible (De Goede, 2019).

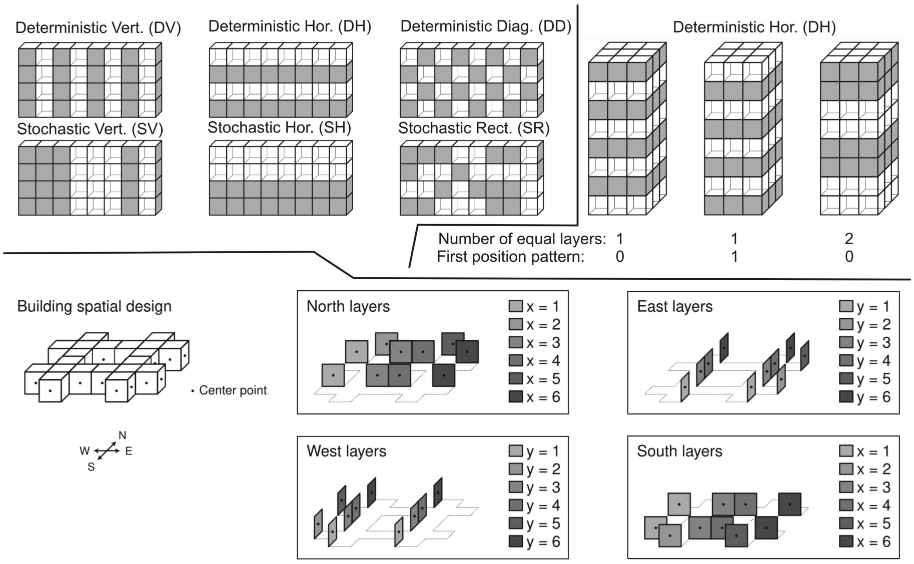


Figure 2. Facade opening patterns (top left), different options for one pattern (top right), four sets of vertical rectangle layers (bottom row).

3.4. ASSIGNMENT OF OPENINGS DURING SIMULATIONS

When the BSD is modified during the co-evolutionary design simulations, as explained in section 3.1, the opening patterns (see section 3.2) have to be managed, for which two procedures have been developed. For the first procedure, "inheritance", for each space surface the surface type (see figure 1, conversion table) is at the start manually defined as open or closed. Subsequently, a rectangle associated with one or two surfaces inherits this information, and is then by conversion rules defined as open or closed. If a particular space is deleted during the simulation, the associated rectangles and their face type (open or closed) are deleted, however, if a space is split into two spaces, these two spaces inherit the surface types of the initial space, and the associated rectangles are then also open or closed. Note that as such the facade opening ratio cannot be controlled. The second procedure, "reassignment", simply reapplies the steps in section 3.2 on every modified version of the BSD, so the facade opening ratio is assured. However, it is possible that the new BSD lacks the number of layers to assure the ratio exactly (e.g. 1 layer with a ratio equal to 0.5), and then the simulation is stopped.

4. Parameter study

A parameter study is performed to demonstrate the effects of facade openings on the spatial-structural optimization of BSDs (via the simulation of a co-evolutionary design process). Two initial BSDs are used, A and B, as shown in figure 3 at the top left, subject to $2\times3\times6\times2=72$ simulations that span all combinations of the following settings: (a) inheritance (IN) or reassignment (RE), see section 3.4; (b) facade opening ratio = 0.25, 0.50, or 0.75; (c) the 6 different patterns in figure 2; (d) design A or B.

4.1. STRUCTURAL DESIGN SETTINGS

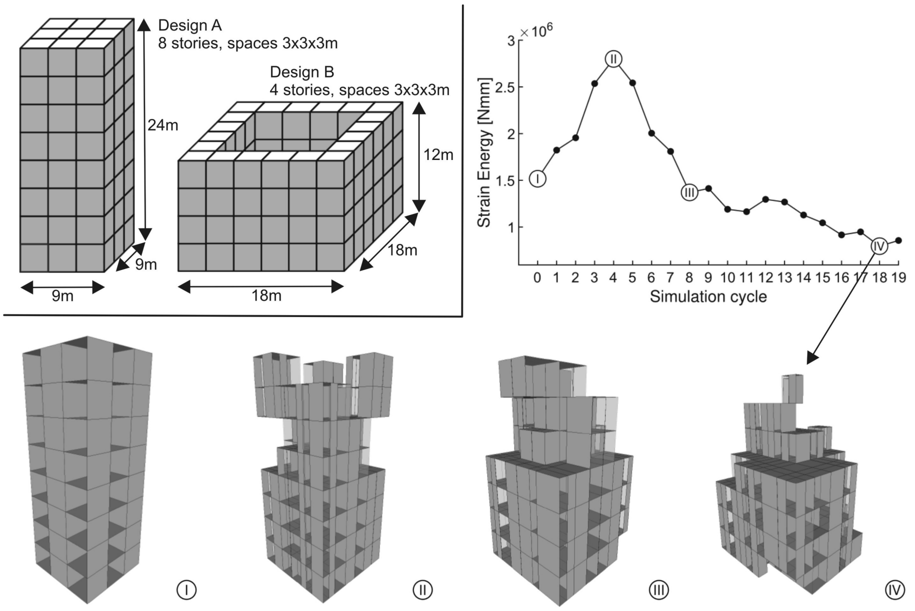
As mentioned earlier, each rectangle with face type “closed” is modelled with a flat shell component. The thickness of this component is 150 mm, the Young’s modulus equals 30000 N/mm^2, Poisson’s ratio is 0.3, and each component is meshed by 3×3 shell finite elements. The open rectangles follow the same approach, but for these the Young’s Modulus equals 0.3 N/mm^2. Horizontal line segments that are located at or below ground level ($z \leq 0$) are constrained for each displacement direction (x-, y-, and z-direction). For each assessment of the structural design, five load cases are applied on the structure via BSD properties: a live load on the horizontal rectangles equal to 0.005 N/mm^2, and for each direction (north, east, south, west) a wind load with either a normal pressure of 0.001, a wind shear equal to 0.0004, or a wind suction equal to 0.0008 N/mm^2, as a function of the rectangle orientation. For each load case the sum of the strain energy over all finite elements is calculated and the total strain energy (the performance) is the sum of the five energy values. Also for each structural component its contribution to the total strain energy is calculated.

4.2. SIMULATIONS

For this parameter study, each simulation consists of 19 cycles, in which for each cycle four spaces, out of 72 (design A) or 80 (design B), are deleted and brought back by splitting other spaces. Minimal dimensions for a space are prescribed, namely 750 mm for either the width or depth. If splitting the best performing space would violate these constraints, the next-best space is tried. Finally, due to space deletion and splitting, BSDs may occur that show (groups of) spaces that are not connected to the ground. To prevent this situation, the BSD is tested by meshing each component with 1 finite element, and applying to this finite element model a single value decomposition, which reveals structural instability (Smulders and Hofmeyer, 2012) and so the unconnected (groups of) spaces. These spaces are neglected for the subsequent finite element simulation, and the first to be deleted in the next cycle. Each simulation is evaluated by: (a) the average structural design’s performance over all cycles, (b) the best achieved performance; (c) the performance after the final cycle. All are normalised with respect to the initial performance and concerning the strain energy, for which a lower value is better (a more stiff structure). Also, the average facade opening ratio over all cycles is calculated, and again normalised for its initial value.

4.3. RESULTS

About one fifth of the simulations ended before finishing the 19 cycles, because of (i) in the case of reassignment, using design B, and for a deterministic horizontal pattern, the opening ratio could not always be assured, see section 3.4. Secondly, at the time of the research, (ii) numerical imprecision sometimes led to intersected spaces, which could not be handled by the implementation. Not ending simulations prematurely, it also happened that unconnected spaces did not trigger the single value decomposition, which led to a dramatic increase of the compliance, in which case that value was neglected. This issue and problem (ii) were solved after the research presented here. Figure 3 at the bottom shows a typical simulation, for design A with deterministic vertical reassignment, and an opening ratio 0.5. The graph at the top right shows that structural performance first decreases (i.e. higher strain energy), but thereafter improves beyond the initial value.



Design A with reassignment, opening ratio 0.5, and deterministic vertical pattern, at cycles 1 (I), 4 (II), 8 (III), and 18 (IV).

Figure 3. Case study designs on the top left, typical simulation shown at the bottom with graph on the top right.

For all 72 simulations the measurements, as presented in section 4.2, are presented in box plots, see figure 4. Normalised average performances show that vertical patterns and the lowest opening ratio (on average across the cycles) perform better than other options. Reassuringly, best performance (within each simulation) plots show that the simulations always lead to better performance, showing they are useful for optimisation. Furthermore, using facade openings allows for better structural performance than for a completely closed building (red dots) and this regardless the use of inheritance or reassignment. End of simulation performance shows a lot of scatter and thus stresses the need for monitoring the simulation process, rather than to trust the final answer. Not displayed here, for inheritance the openness decreased, whereas for reassignment the openness kept reasonably constant, as expected (De Goede, 2019). Results show that inheritance led to 86% of the simulations corrected by the singular value decomposition procedure, whereas for reassignment this was only 46%. The hypothesis here is that reassignment leads to the continuation of more regular patterns along the cycles, and so a more regular pattern of space deletion, whereas inheritance leads to an increasingly free formed opening pattern during the simulations, promoting unconnected spaces. Finally, it should be noted that even the best peformance may be a local minimum, due to the heuristic search. Global search (e.g. with an evolutionary algorithm) may reveal global minima.

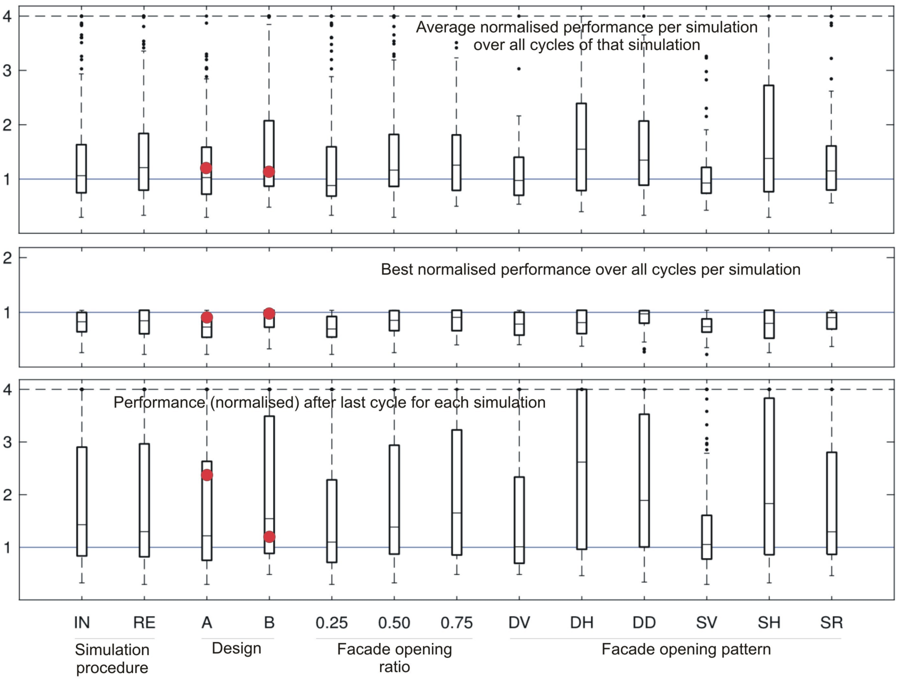


Figure 4. Results of all simulations shown in box plots. Red dots indicate reference simulations with no openings at all.

4.4. DISCUSSION

In the parameter study, only one structural grammar has been used. Other structural design types, made possible by different grammars, could change the outcomes of the study significantly. The same applies to variations of simulation settings, i.e. the number of cycles per simulation, the number of spaces deleted per cycle, and the minimal space dimensions.

Data not presented in this paper show that a decreasing facade opening ratio leads to more improvement of structural design performance over the cycles, due to the reduction of building storeys. It appears that openings “weaken” a space as they do not allow for structural components at the opening, and so surrounding components are strained more, leading to a higher strain energy for the space. Spaces with openings are thus less likely selected for deletion. Besides, in each cycle 4 spaces are deleted, less than a storey for both design A and B, and thus spaces will be left at the top floor. Also it can be shown that if the opening ratio is higher, these left spaces at the top floor will have more open rectangles, thus increasing the strain energy, and avoiding deletion, and thus the reduction of storeys.

For designs without openings, sometimes spaces directly under the spaces at the top floor are deleted, leaving some top floor spaces cantilevered. This increases the strain energy in these top floor spaces significantly, once again avoiding the reduction of the number of storeys. This indicates the importance of selecting the appropriate number of spaces to be deleted, or the need for more globally operating design variables.

In this research, only the effects of facade openings on the structural performance of a BSD have been investigated. However, the facade openings have been introduced first of all to include lighting and improve thermal performance assessments in future co-evolutionary building design simulations. However, for lighting and thermal performance the effects have not been studied yet, and some designs as shown in this paper may not be useful from the perspective of these disciplines.

5. Conclusions

An existing toolbox, which among others can be used to simulate co-evolutionary spatial-structural building design processes, has been extended by (i) the inclusion of facade openings in the building representation; (ii) a generator to design facade opening patterns; (iii) two procedures to manage the facade openings during modifications of the spatial design; (iv) a load panel to transfer wind loads on the facade “openings” to the structure.

A parameter study has been carried out to study the effect of facade openings on spatial-structural building optimisation via co-evolutionary design simulations. All combinations of settings (BSD, opening management, opening pattern, opening ratio) have been simulated. It is shown that vertical facade opening patterns with a limited opening ratio improve spatial-structural optimisation, by enabling the number of storeys to be reduced. Inheritance did not give control over the opening ratio, and led to many cases of unconnected spaces.

The research has shown that the number of spaces to be deleted in one cycle of the simulations is critical for the results, and more global operating modifications should be studied.

The reassigment procedure is considered for an upcoming project, where spatial-structural-thermal-lighting building optimisation is investigated, including non-rectangular spatial designs. This will allow for the investigation of the effects of facade openings on structural, thermal, and lighting design. Furthermore, multi-disciplinary optimised BSD's can be found, and related design processes can be supported.

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