12 Coupling Between a Building Spatial Design Optimisation Toolbox and BouwConnect BIM

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Abstract
This paper presents a framework in which a building spatial design optimisation toolbox and a building information modelling environment are coupled. The coupling is used in a case study to investigate the possible challenges that hamper the interaction between a designer and an optimisation method within a BIM environment. The following challenges are identified: Accessibility of optimisation methods; Discrepancies in design representations; And, data transfer between BIM models. Moreover, the study provides insights for the application of optimisation in BIM.

Keywords
Optimisation • Building information modelling • Building spatial design • Structural design • Building physics

12.1 Introduction

Optimisation of building designs has gained significant focus in recent years. One of the reasons is that design objectives have become more demanding and higher in number, making it more difficult for human engineers to manage and oversee a building design process. To make matters worse, the built environment is seeing an increase in disciplines that each have their own effect on the design objectives.

Building Information Modelling (BIM) aims at structuring data, such that the different disciplines involved in Architecture, Engineering, and Construction (AEC) projects can work together efficiently. However, this data structure is complex, which makes it difficult to apply optimisation techniques on BIM models. For example, the number of design variables may change when modifications are made to a BIM model. As a consequence, it is hard to define frameworks for optimisation algorithms in a BIM context.

This paper explores an integration of optimisation techniques into design processes that use a BIM environment. A framework that couples a building spatial design optimisation toolbox [5] to a BIM environment is proposed in Sect. 12.2

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Accordingly, a case study to investigate the interaction between a designer and an optimisation method is presented in Sect. 12.3. Finally the conclusions and an outlook are given in Sect. 12.4

The following topics are discussed in the remainder of this section: building design optimisation in Sect. 12.1.1; optimisation and BIM in Sect. 12.1.2; and finally a motivation for the presented work in Sect. 12.1.3.

12.1.1 Building Design Optimisation

Building design optimisation research is a well defined field with different approaches, a thoughtful overview of the field is found in [10]. In this field, researchers try to hand support tools to designers, e.g. for feedback on design decisions in early stage design [12]. Others focus more on the application of state-of-the-art algorithms, as is carried out in [7]. Also parametrisation of designs and the impact of parameters [9] are well treated topics in the field. However, application of optimisation techniques in the built environment is not common. Therefore, the authors of [11] investigate how to make current optimisation and design techniques available to designers and policy makers. But, for industry, application of such techniques may not be straightforward. Usually, research on building design optimisation is presented with (sometimes academic) examples, but it is rarely studied how the methods are applicable to- or experienced by industry.

12.1.2 Optimisation and BIM

BIM is accepted more and more as a standard in the AEC industry [1]. For the application of building design optimisation it is thus important that it is well fitted within a BIM context. Examples of optimisation in BIM environments can be found, usually BIM models are parametrised, e.g. [2]. A parametrised BIM model can however be unsuitable for optimisation, e.g. because parameters appear or disappear after the model is modified. Such behaviour can be dealt with by defining meta parameters, which describe the value of the dynamic parameters in the problem. This is for example carried out in [6], in which a structural design is created for a BIM based building spatial design by using different functions as a meta parameter to generate structural parts in the BIM model. Optimisation tasks that are carried out within a BIM environment are, however, almost always limited by the BIM data structure. As a consequence, also the design search space will be limited when a BIM environment is used.

12.1.3 Motivation

Building design optimisation is a well developed field of research, however it is not widely used in industry. BIM is the de facto standard for building design modelling, but its complex data structures make it hard to apply optimisation methods. It is desirable that optimisation methods become more accessible, preferably for modern standards like BIM.

The work in this paper is part of a wider research scope, in which the multi disciplinary optimisation of building spatial designs is researched. The research that has been carried out so far within the latter scope is academic, and thus somewhat removed from the building design practice. In this paper, the aim is to identify the barriers that keep designers from using optimisation methods in a BIM context. To that purpose, here a study is conducted on an interaction between a designer and an optimisation method that has been developed in the wider research scope.

12.2 Framework

First, an optimisation toolbox for building spatial design, structural design, and building physics design is introduced in Sect. 12.2.1. Second, a commercial BIM environment that is used in the Dutch built environment is introduced in Sect. 12.2.2. Finally, a coupling between the toolbox and the BIM environment is presented in Sect. 12.2.3.

12.2.1 Optimisation Toolbox

A detailed description of the building spatial design optimisation toolbox is given in [5]. Here, a short outline of the relevant parts of the toolbox is given.

Building Spatial Design Representation The representation of a design determines the parameters that can change the design. Therefore, it also affects the type of optimisation methodology that can be applied. In the toolbox, a building spatial design is defined as a collection of spaces. Two representations have been implemented in the toolbox, both of which are limited to represent only cuboidal spaces in an orthogonal grid. One representation uses the so-called *supercube* (SC), in which cells are defined by a 3D orthogonal grid and each cell can be controlled individually to be active or inactive for a space in the building spatial design, see Fig. 12.1a. The SC representation can be expressed in mathematical terms, and is therefore suitable for evolutionary algorithms (EAs). The other representation uses two sets of three parameters per space, i.e. the location (x, y, and z) and the dimensions (w, d, and h). Spaces can be moved and dimensioned freely, the representation is—in the context of the toolbox—therefore termed the *movable and sizeable* (MS) representation, see Fig. 12.1b. This representation is relatively easy to interpret for humans, which makes it suitable for heuristic design rules that are defined by designers and engineers.

Design Grammars In order to obtain discipline specific performances from a building spatial design it is necessary to evaluate a model for that discipline. Such a model can be derived from a building spatial design using a design grammar, i.e. a set of design rules. These design rules use spatial and geometric relations within the spatial design, e.g. internal or external walls, to decide what is modelled at different locations in the discipline specific model. The toolbox is equipped with a design grammar that can generate a building structural model. This can be used to evaluate displacements, reaction forces, stresses, and strains. Moreover, a design grammar for a building thermal model is implemented in the toolbox. This can be used to evaluate the heating and cooling energy for a space that is required to keep the temperature within a predefined (comfortable) range.

Optimisation Methods In previous work, two different optimisation approaches have been developed within the context of the toolbox. First, an approach that uses a simulation of co-evolutionary design processes, which is presented in [8]. Second, an approach that uses an EA, which is introduced in [3] and which is further developed to what is presented in [4]. The first approach uses the MS, and the second uses the SC-representation to describe a solution.

12.2.2 The BouwConnect BIM Environment

BouwConnect is a Dutch commercial BIM environment (www.bouwconnect.nl). It consists of a product library and a building model environment. The product library contains information about nearly all building products that are available on the Dutch market. It is structured such that products are composed of data objects that describe part(s) of a product, e.g. material, shape, and function. A product in the library contains 2D- and 3D-CAD models and also information on costs,

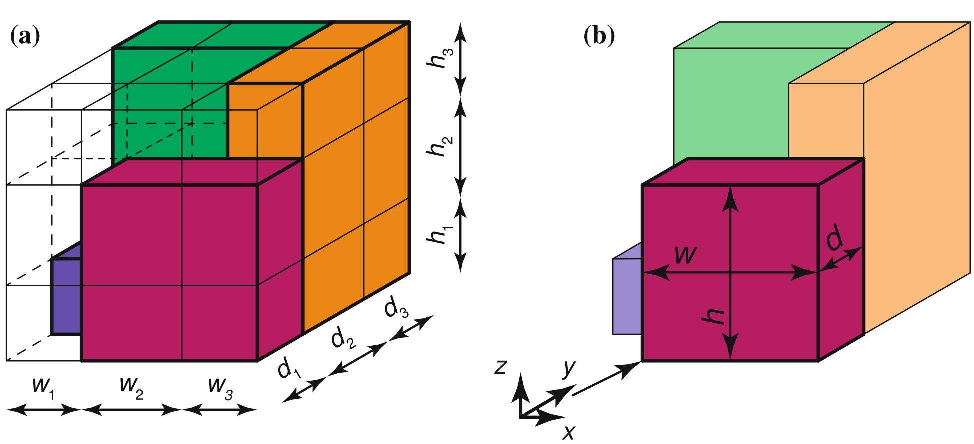

Fig. 12.1 The two building spatial design representations in the toolbox, different spaces are each indicated with a color. **a** Depicts the *supercube* representation with active (filled) and inactive (empty) cells in a 3D orthogonal grid. **b** Depicts the *movable and sizeable* representation, in which individual spaces can be moved freely

pictures, descriptions, and suppliers. Products can be placed/linked in a building spatial model via the building model environment. Using this environment, calculations and checks regarding energy, daylight, ventilation, fire security, and so on can be carried out. Both the product library and the building model environment can be linked (two-way) with other software (e.g. Revit and AutoCad), Industry Foundation Classes (IFC), and local Dutch software.

12.2.3 Coupling

The coupling between the toolbox and the BIM environment is realised by means of the Extensible Mark-up Language (XML). An XML file holding data on a building spatial design model can be parsed by both software environments. Parsing the file with the toolbox results in a model in the MS representation. If the file is parsed in the BIM environment it results in a collection of building elements that have been assigned to spaces. Each building element owns a geometry, which is an ordered list of 3D vertices ($x_1, y_1, z_1, x_2, y_2, z_2, x_n, y_n, z_n$). As such, a space's geometry is defined by that of its building elements and not by one of its own. The XML data structure, which is similar to the data structure of the BIM environment, is illustrated in Fig. 12.2. The presented data structure is implemented such that it can be extended, e.g. with the data that is generated by the design grammars. It should be noted that in Bouwconnect and the XML file, in contrast to the toolbox, a space is not a direct representation of geometry.

12.3 Case Study

This section presents a case study in which an optimisation result is used to modify a building design. The case study is followed by a discussion.

12.3.1 Design Process

Incorporating optimisation into a BIM based design process is here proposed as follows. First, a design that has already been developed in the BIM environment is selected. Accordingly, the design is exported to and optimised in the toolbox.

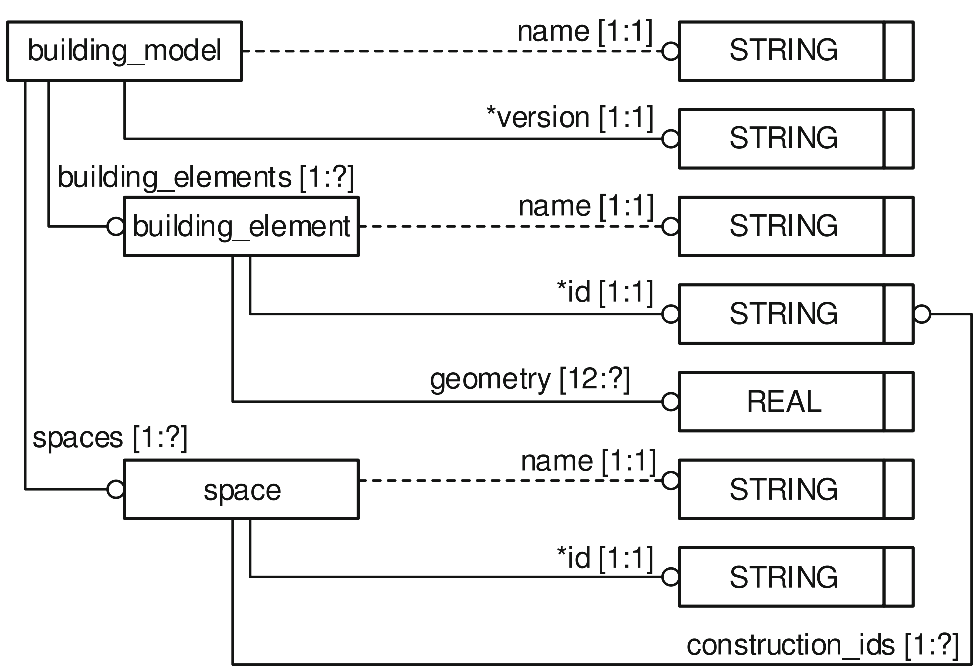

Fig. 12.2 Data structure of the XML file, visualised in EXPRESS-G

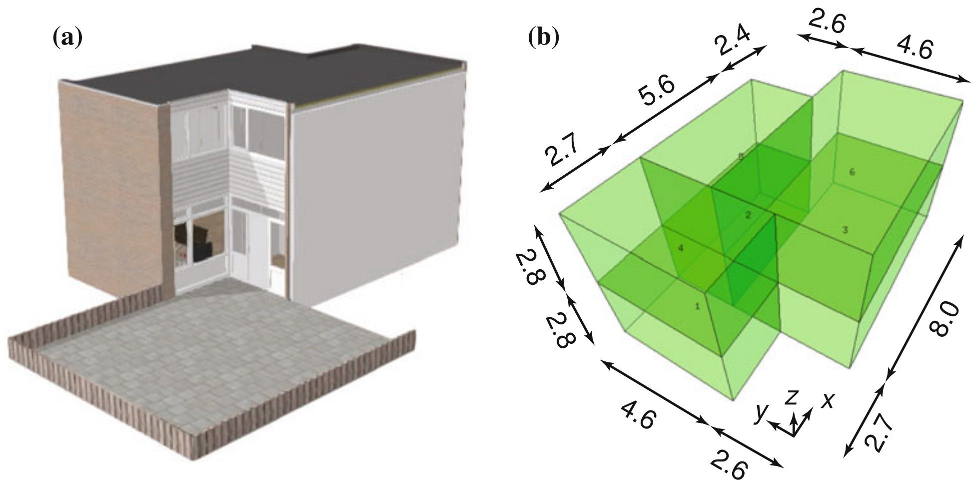

Fig. 12.3 The selected design. **a** Shows the visualisation in BouwConnect. **b** Shows the visualisation in the toolbox together with the dimensions (in [m])

Thereafter, the selected design is modified based on the optimisation results. The new design is then compared with the original.

Selected Design Fig. 12.3 presents the design that has been selected for the study. It has been selected for its rectangular properties, because the toolbox can only represent designs with cuboid spaces. It should be noted that the design is a terraced house, the light grey wall in Fig. 12.3a and the wall adjacent to it are shared with similar terraced houses.

Conversion Although automated, the conversion from BouwConnect to the toolbox is limited. This limitation results from the fact that geometries of building elements in BouwConnect extend beyond rectangular geometries, however the toolbox does not. Therefore, for this study the vertices of all geometries in the XML file are listed together. Accordingly, by mapping that list, the corner points of spaces are selected visually. Spaces are then manually defined in a representation that is readable for the toolbox, resulting in the design of Fig. 12.3b.

Optimisation For optimisation, the EA in the toolbox is used and the settings for the design grammars and the algorithm are borrowed from [4]. From that study, the SMS-EMOA-SC algorithm is selected because in the study it performed best.

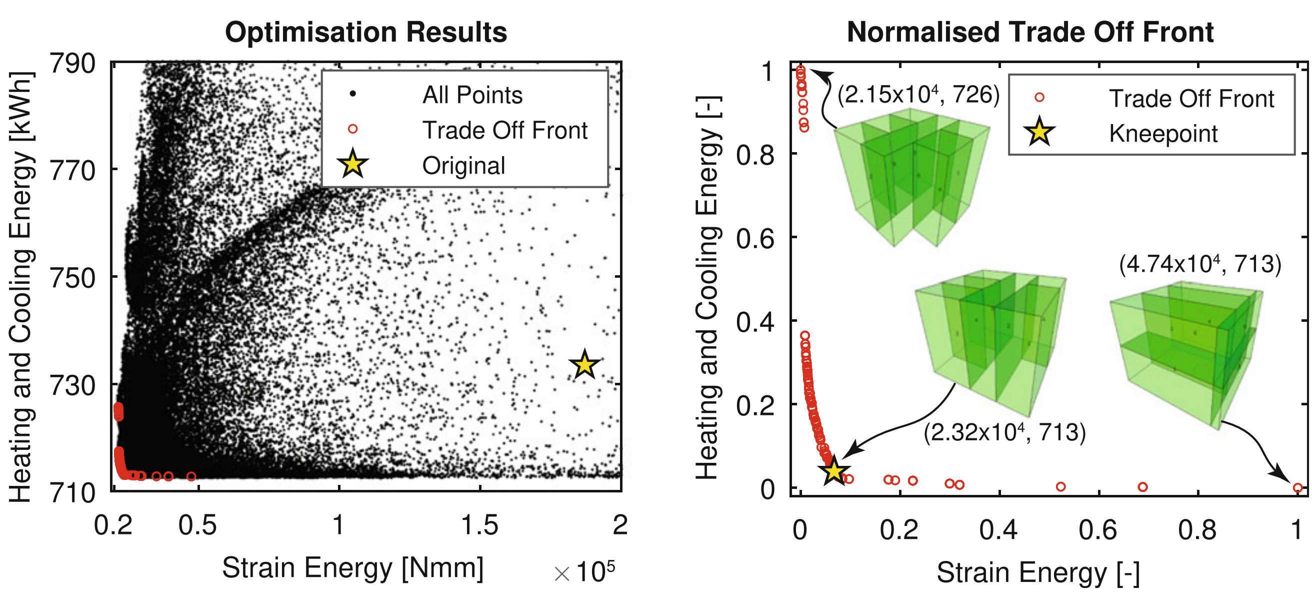

Fig. 12.4 The left graph shows all evaluated results and the trade off front (over all 10 runs), note that outliers are not shown (<5% of all solutions). The right graph shows the normalised trade off front and some designs and their performances: The best structural- (0, 1); The best thermal- (1, 0); And, the kneepoint performance

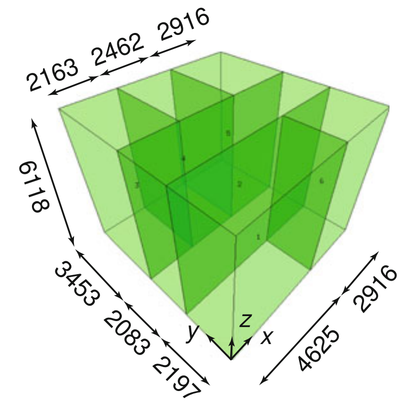

Fig. 12.5 The design with the kneepoint performance, visualised in the toolbox and an indication of the dimensions (in [mm])

Table 12.1 Comparison of characteristics between the original and the optimised design

Source[a]	Characteristic	Unit	Original design	Optimised design
TB	Volume	[m^3]	357	357
BC	Floor area	[m^2]	118	59
TB	Strain energy	[N mm]	1.871e5	0.2322e5
TB	Heating and cooling energy	[kWh]	733.5	713.3
BC	Total annual energy use[b]	[MWh]	32.82	25.45
BC	Energy index[b]	[−]	1.85	2.03

[a]TB for toolbox and BC for BouwConnect; [b]According Dutch regulation NEN-7120

Two objectives are set, i.e. minimisation of strain energy and minimisation of the heating and cooling energy. Equality constraints have been defined to enforce a constant volume, cuboid spaces, and no vertical gaps between spaces. Also, inequality constraints have been defined to bound space dimensions. The algorithm is given an evaluation budget of 10,000 and it is run ten times to decrease dependencies of the result that may be caused by stochastic processes such as initialisation and mutation. Problem specific optimisation settings are derived from the selected design (Fig. 12.3b): 6 spaces; volume of 357 m^3; and a supercube of $3 \times 3 \times 2$ (w, d, h) is used. The optimisation results are given in Fig. 12.4, where the kneepoint is determined as follows. All values of the trade off front—over all runs—are normalised to a [0, 1] interval between the minimum and maximum found values in each objective. Accordingly the kneepoint is defined as the normalised point with the smallest (Euclidean) distance to the origin [(0, 0) for the 2-dimensional case].

Design Modification In this step, in BouwConnect, the original design (Fig. 12.3) will be modified using the optimal design, i.e. the design that corresponds with the kneepoint performance, see Fig. 12.5. The following procedure is followed, first, the kneepoint solution is imported from the toolbox into the BIM environment. Accordingly—using the imported design data—some data of the original design is modified such that an energy performance calculation within BouwConnect can be performed. Although possible, the procedure does not entail a full modification of the original design, due to time restrictions and—for the study at hand—it would only add a visualisation. During the modification procedure, the designer had to make design decisions, some of which are: The walls parallel to the y-direction, are in the optimised design assumed to be fully shared with other buildings; As a consequence, also the orientation of some windows had to change; Functions of spaces were redistributed.

Comparison Both the original and the optimised design are compared by using characteristics that were generated by both the toolbox and BouwConnect, see Table 12.1. First to notice is a 50% reduction of floor area in the optimised design, but the volume is unchanged due to the optimisation constraints. Moreover, the two objectives in the toolbox (minimal strain energy, and heating and cooling energy) have successfully been improved. This improvement also leads to a smaller total annual energy use according to the calculations by BouwConnect. However, the energy index, which is used to asses a building's energy efficiency, becomes higher (higher being worse) for the optimised design. This is caused by the reduction of floor area in the building, because—regarding efficiency—the energy use per useful floor area has increased (32.82/118 = 0.28 MW h m^{-2} has become 25.45/59 = 0.43 MW h m^{-2}). Note that in Table 12.1, the heating and cooling energy from the toolbox results from a simulation of three hot and three cold days. Whereas, the total annual energy use from BouwConnect is an estimate for a full year but it also includes energy use by ventilation, hot water, and lighting.

12.3.2 Discussion

Use of optimisation methods by industry is desirable, and—considering modern standards—such methods should be well incorporated in a BIM environment. A case study has therefore been conducted in order to identify the challenges and barriers while attempting to integrate an optimisation method for building spatial designs into a BIM based design process.

Looking at the results in Table 12.1, a critical remark may be that the optimised design is not practical. Although less energy is needed for exploitation of the building, there is a significant reduction in useful floor area. A building's floor area is an important measure for practical uses of a building like fitting furniture, selling price, and comfort. Optimality can, in this case, thus be questioned. It should, however, also be noted that a lesson can be learned, albeit obvious. Namely, in order to reduce energy use, one may have to consider to reduce the floor area of a design. Nonetheless, it would be desirable to introduce an inequality constraint in the EA to ensure a minimal floor area. Which in this case is a non trivial task for a designer, because the used optimisation method is highly tailored to the problem. Implementation of such a constraint requires knowledge of the algorithms that are used in the method.

Connecting the toolbox and BouwConnect via the proposed coupling did not lead to a seamless conversion between the two environments. This is mostly caused by the differences in the geometric representation of a design. BouwConnect is based on geometries of building elements, as such, a space's geometry is defined by that of building elements and not by its own. An approach that is not uncommon in BIM data structures. The toolbox uses 3D geometries to define spaces, and if applicable, defines building elements by using (parts of) their surfaces. This discrepancy requires a solution in either the BIM environment or the optimisation method, in order to allow for a seamless conversion.

Data transfer between models is another issue that must be addressed. In the case study, the optimised design could not inherit some of the features in the original design. Transferring data between the optimised and the original design thus requires design decisions, a process that is currently labour intensive. A method that can automatically inherit data from another BIM model based on similarities could be useful here. Such a method could also be extended, in order to present a designer with design decisions when certain features are not present in the new model. Not only would this method be useful for optimisation, it could also be used to initialise a new model for buildings that show strong similarities with buildings that have already been modelled.

Finally, it should be noted that the case study was limited to importing an optimised design and assigning its properties to another design. Findings may, therefore, not be generally applicable to optimisation in BIM environments. However, they can serve as starting points for optimisation of BIM models.

12.4 Conclusion and Outlook

In this paper, a coupling between an optimisation research toolbox and a commercial BIM environment has been presented. Using the coupling, a case study has been performed in which an optimisation result has been used in a BIM design process. The study showed that optimisation techniques should be—to some extent—adjustable by the designer. Moreover, it was concluded that discrepancies in problem representations require a thoughtful conversion between the two. Also, an automated transfer of data between BIM models based on similarities between the models would be beneficial. The findings from this study may be used to extend the optimisation research toolbox or the commercial BIM environment to further investigate the integration of optimisation methods into BIM environments. The study can also provide starting points for other optimisation approaches of BIM models.

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