Improving Design using Autonomous Spatial and Structural Generators

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Abstract. *During a building design process, a structural designer transforms a spatial design into a structural design and this structural system can be improved by optimisation methods or expert views of other structural designers. The improved structural system allows the architect a new spatial design, which can be transformed or altered again by the architect. This design cycle can be repeated several times and is defined as interaction of spatial and structural design. Case studies are used to demonstrate that this interaction occurs in practice and is needed to improve building quality. This paper presents a program with more or less autonomous spatial and structural generators. Each generator will facilitate one direction in the interaction process. Then using both consecutively leads to a design method that provides interaction between spatial and structural design. For the spatial generator, named "room positioning with structural constraints" a space allocation technique is used including constraints that handle structural boundary conditions. A zone generator based on pattern recognition and shape grammars handle the structural design. A Prolog-2 program was developed to demonstrate the application of the two proposed generators. "Zone generation" is performed per building storey and thus represents a horizontal two-dimensional procedure. Similarly "room positioning with structural constraints" is a planar vertical operation. In future these procedures can be made three-dimensional.*

Keywords. *Spatial design, structural design, interaction, case study, data model.*

Introduction

During a normal building design process, an architect transforms an architectural plan into a spatial design. This spatial design is then presented to the structural designer who develops a structural system for it, figure 1 on the left. Often, the structural system is fine-tuned in cooperation with the architect to fulfil detailed architectural requirements and to fit other building requirements like building services.

Many attempts exist to develop an early design computer tool for the building design process. These attempts are often focussed on spatial or structural design solely, and assume a strong directional activity from spatial to structural design as is also observed in practice, figure 1. For spatial design, a good overview of computer tools was presented (Liggett, 2000). In this work, the history and future of space allocation is treated. A recent development is the use of physics of motion to space allocation (Arvin, 2002) and even more spectacular, three-dimensional massing designs can be generated (Wang and Pinto Duarte, 2002). More connected to the research that will be presented here, a model of visual reasoning in design was developed that can be used to alter spatial designs as proposed in this paper (Oxman, 1997). For structural design tools, the focus on the structural design is very detailed, for example one truss system in (Anumba et al, 2002) or the more determined phases of the structural design are taken into account (Sacks et al, 2000). The early structural design process is not often subject to research but is available via books (Salvadori, 1986), and more recently by computer aided tools (Abdelmawla et al, 2000; Vassigh, 1999).

The building design process can also be observed differently: A structural designer transforms a spatial design into a structural design and this structural system can be improved by optimization methods or expert views of other structural designers. The adjusted structural system allows the architect a new spatial design, which can be transformed or altered again by the architect. This design cycle is defined as interaction of spatial and structural design, figure 1 on the right.

Other researchers have shown successfully that a building design project can be seen as a sequence of views and dependencies (Haymaker et al, 2004) and concept formation in spatial design is suggested to be dependent on the recognition of patterns in the representation of designs. This is demonstrated by Gero in an evolutionary system (Gero, 1998) that can also be valid for a combination of spatial and structural designs.

In this paper, we present an early design tool based on interaction of spatial and structural design. We know of a few research projects that are strongly related to this approach. The first project manages agents that are classified into “generators” and “critics”. The generators develop the design whereas critics evaluate the current design and make redesign recommendations. Interaction of spatial and structural design is not specifically defined but it is hoped that the managing of spatial and structural agents will yield interaction automatically (Fenves et al, 1994). The second project

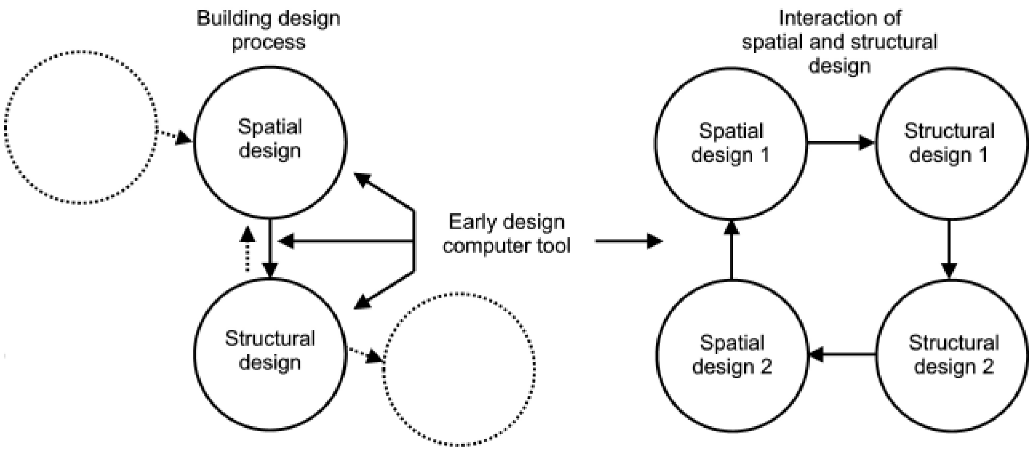

Figure 1. The building design process and interaction of spatial and structural design.

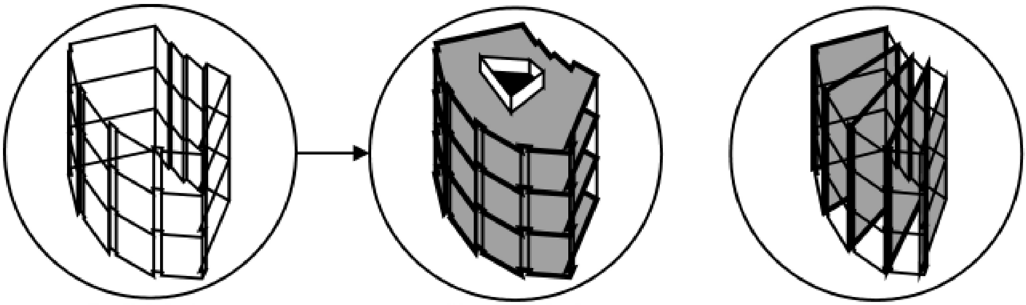

Figure 2. Chosen structural design does not follow spatially suggested partition.

proposes a methodology to synthesize structural systems within a spatial design (Mora et al, 2004). The building design process is regarded as more or less linear: the structural system follows the spatial design, however some feedback from the structural system towards the spatial design is possible. The software prototype that is presented is a helpful tool for the designer, but does not take over design steps. For instance, the zoning process, also recognised by us as a very supportive idea (Hofmeyer, 1994), in which the designer takes groups of spatial entities together for which a structural system is designed, is completely left to the structural engineer. The third project proposes a method for negotiating architectural design across domains (Haymaker et al, 2000). The design examples shown are interesting although the structural domain is treated very limited, which can be understood because many other domains are involved. For finding appropriate data models, a research project was presented that separates the building object data in an object database from a specific design that is handled by a product database (Khemlani et al, 1998). It uses spatial and structural building design data. Finally, the building design process has been investigated in order to generate specifications for a building design tool (Meniru et al, 2003). Multiple levels of abstraction, element interaction, and design overview are among the specifications found. However, creative systems that present new and innovative ideas to the designers are not mentioned: "No designer is willing to delegate power to the computer ...". The work in this paper should not be seen as taking power from the designer, but as equipping a designer with a creative tool to enhance his possibilities.

Case studies

In this section, three types of case studies are used. First of all, a real world project is presented (Hofmeyer, 1994). Then, student design work is used as a second type of case study. And as a last type, a research project is shown that investigates the influence of a structure type to the spatial design.

Real world project, no logic for structure follows form

The office building "De Centrale" in The Hague, The Netherlands, was designed as shown in figure 2. The architect made a spatial design for a 25 storey building (three storeys are shown) that suggests that the building is composed of four vertical elements. The structural designer directly transformed this spatial design into a structural design of a concrete core with concrete floors, which span from the core to the facade columns. For the concrete floors, several types were investigated;

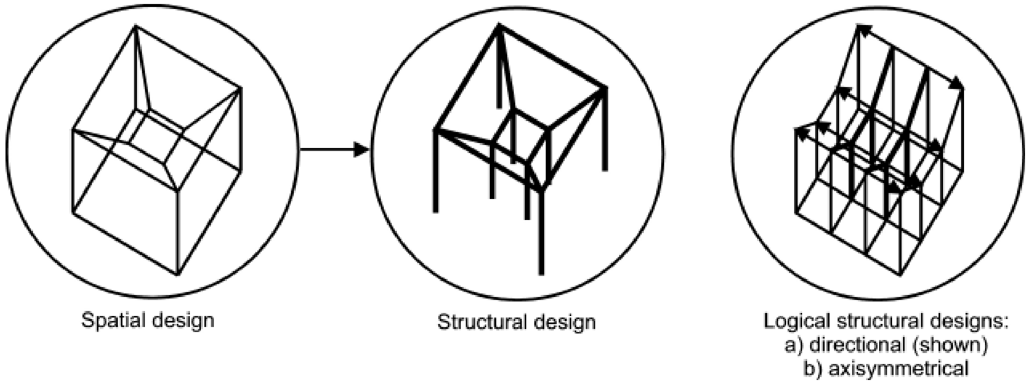

Figure 3.For this spatial design a directional (shown) or axisymmetrical structure is suitable. Both require serious reconsideration of the spatial design.

finally a half-slab design was used.

This project shows a direct transformation from spatial to structural design (no interaction). The chosen structure is not logically linked to the spatial design. Stability walls with infill floors or even a bundled tube-structure as used for the Sears Tower in Chicago would have been a more expensive but also a much more logical solution.

Greenhouse student project, structure follows form

For a student project at our department of architecture, building, and planning, students were asked to design a greenhouse situated in a castle garden. A greenhouse normally has a strong relationship between spatial and structural design. What we observed is that students always start with an arbitrarily spatial design, after which an enormous effort is needed to design a structure that can fit the spatial design, see figure 3. We then suggest the students to start with a good structure and let the spatial design follow.

Critics will suggest that this is not the way in which practice works, but we will explain our method: In practice, almost every spatial design can be quite elegantly transformed into a structural design. However, the set of possible spatial designs is infinitely large and most of them -by their very nature- are not suitable for a structural design. Thus, it is very likely that the architect pre-selects

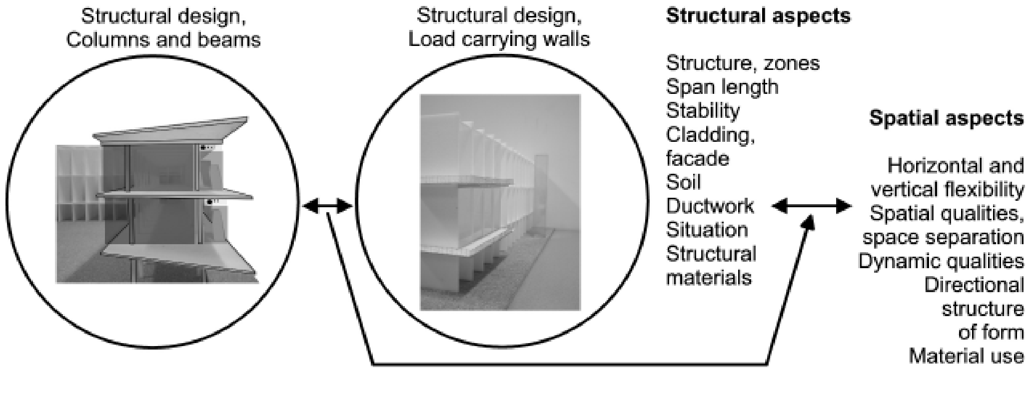

Figure 4. Research project uses design results to connect structural and spatial aspects.

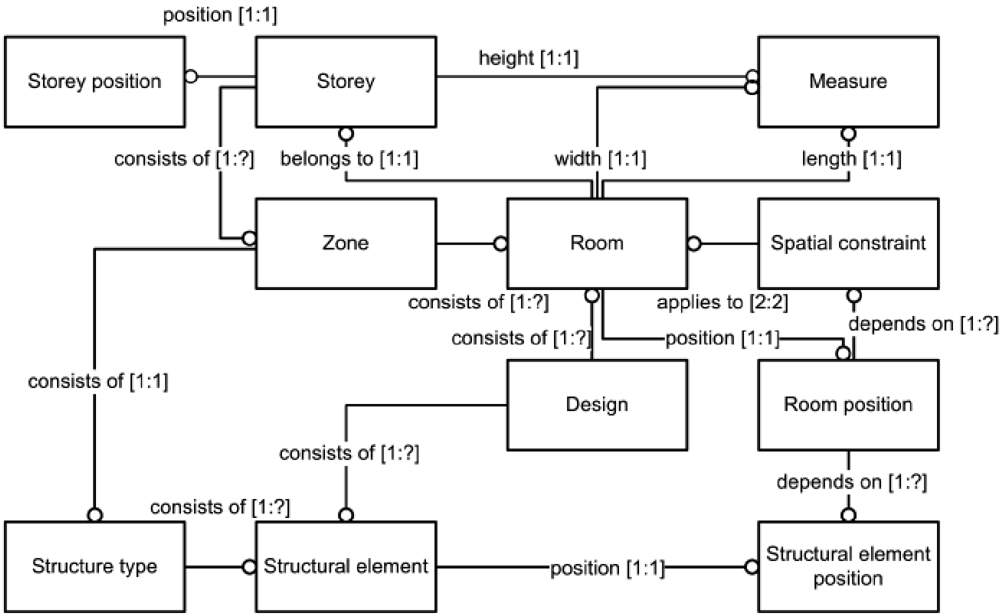

Figure 5. Program's underlying data model.

only spatial designs that can be transformed into a structure. To make this process explicit, we start the design process with a structure instead of a spatial design.

Research project, form follows structure

That a structure type can seriously influence an architectural design was shown by a research project (Roebroek, 2005). For this project, two different structure types were used: (1) columns and beams and (2) load carrying walls, see figure 4 on the left. Making several building designs, a study was made on the relation between several structural and spatial aspects, figure 4 on the right.

The case studies show that in practice a spatial design is directly transformed into a structural design, but that does not mean the most logical structure will be chosen. Students imitate this behavior, but their chosen structure is unusable and thus redesigning the spatial design is necessary. Therefore, it is assumed that interaction between spatial and structural design is a subconscious process, via parallel lines of thought (Lawson, 1997), and skilled by education. The research project shows that a structure can have a large influence on the architecture. In the case where a spatial design cannot directly be transformed into a structural design and thus a structure type has to be chosen first, this is a key issue.

Program

The case studies show that interaction of spatial and structural design is used on a conscious level neither by professional designers nor by students. To start research on this subject, a prototype program was made, which will be presented in this section. The transformation from spatial design to structural design is provided by the procedure "zone generation" whereas the procedure "positioning rooms with spatial constraints" provides an initial step from structural design to spatial design.

For the program, assumptions were made to make implementation possible: It is assumed that a building comprises storeys. This is very often the case, but not necessarily. The building substructure is assumed to have an infinite stiffness. All rooms are rectangular with specified surface dimensions. And finally, for the structure, only a limited set of structural types are used and structures are only designed for dead load.

The underlying data model of the program is shown in Express-G notation in figure 5. A design consists of several structural elements and rooms. A set of rooms can be seen as a zone, for which a structure type can be generated. The position of a room depends on spatial constraints between rooms (i.e. two rooms should be adjacent) and the position of structural elements already generated.

The program starts with making a single storey spatial design, using a space-allocation technique and taking into account the room properties and spatial constraints. Hereafter, the procedure “zone generation” is applied. This horizontal two-dimensional procedure uses pattern recognition to find zones in the spatial design. A zone can incorporate multiple rooms and has a shape that can be recognized by the structural designer as structurally feasible (Hofmeyer, 1994). In this case, only rectangular zones are used.

For each zone, a structure type is chosen, generating structural elements (Orton, 1988) and their position via a shape grammar. Structure types available are (1) concrete cast-in-place walls with one-way solid slabs (2) steel single-storey beam and post systems with cold-formed steel decking (3) wooden trussed rafters without purlins and (4) a double layer space frame supported by concrete precast columns. For the next step, the planar vertical procedure “positioning rooms with spatial constraints” is used. The storey positioned above the structure is designed. Again a space-allocation technique is used, but now structural element positions form an additional constraint, like the spatial constraints did for the first spatial design. In the mean time, the program determines relevant building properties, for example the weight of structural material. This data can be used during the interaction process between user and program.

Figure 6 shows an example of the design process that is followed by the program. The architectural program consists of two rooms that should be adjacent and one of the possible design solutions for this is shown in the top left, design number 1. Recognizing zones in the spatial design, it is found that a structure can be made of the total spatial design: A double layer space frame supported by concrete columns, design 2. However, the user interacts and prefers another solution that is offered by the program: Two concrete walls with a one-way slab for the first room and a beam and post system with steel decking for the second room, design 3. Based on this information, the spatial design procedure is restarted and the third room is positioned such that the underlying structure is as helpful as possible in supporting the room.

The example shown is arbitrary. Because the program is written declaratively and implemented using Prolog-2 for windows, all possible design solutions can be generated, only limited by user interaction and structural systems available in the

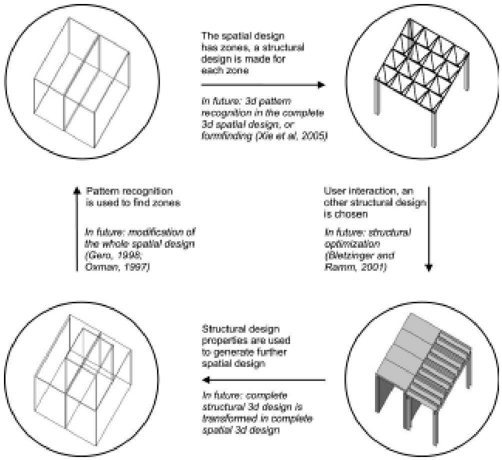

Figure 6. Program example, compare with figure 1 on the right (italics are proposed future work).

structural grammar.

Conclusions and future research

More than just presenting a prototype program, this paper wants to stress the need and possibility for using other abstractions of the building design process than those that seem to be the most logical. It is proven by other authors (Gero, 1998; Oxman, 1997) that very complex or unexpected design algorithms lead to successful design tools and also seem to enclose some of the more underlying thoughts we have during a design process. A spatial design and a structural design are two views of one entity. Without a structure, a spatial form can not exist and a structure automatically creates some spatial form. To use this knowledge in order to help designers and provide them with new and creative results, an early design computer tool cannot be based on the assumption that a simple linear transformation exists from a spatial to a structural design.

The prototype program presented here shows a cyclic transformation process between spatial and structural designs as shown in figure 1 on the right and figure 6. The spatial to structural transformation is performed per building storey and thus represents a horizontal two-dimensional procedure. Similarly, the structural to spatial transformation is a planar vertical operation. Figure 6 shows possibilities for future improvements. It would be interesting to see the two existing procedures to be three-dimensional and acting on the complete three-dimensional building design. The technique of form-finding (Xie et al, 2005) is suitable to find a structural shape for a spatial form and can be used as an alternative. Techniques exist to optimize structural systems (Bletzinger and Ramm, 2001) and these techniques, normally used for one structural system, could also be used on the building level. To vary spatial design, the research mentioned in the introduction could be helpful (Gero, 1998; Oxman, 1997).

Results of research on data models, design methodology, and expert systems have to be taken into account during further development of the idea and the program presented here. However, the program is no replacement for an expert system. It is used to generate creative solutions within the spatial and structural design space and as such it can be used within existing design systems or methodologies. We definitely believe that a powerful pattern recognition algorithm -changing spatial designs into structural designs- can be, besides a single commercial interesting tool, one of the generators in a multiple spatial-structural design cycle that generates creative solutions to the designer, even if this design cycle is not representative for a normal design process at first sight.

While the pattern recognition in this prototype is based on recognizing geometrical patterns of spatial layouts and structures, the recognition of semantic information in a design model may further enhance the potential of the interpretation process. Research by Fridqvist has demonstrated the feasibility of pattern recognition in abstract feature models (Fridqvist and Van Leeuwen, 2001). This technology can be used to assist designers by recognizing the semantics of their models and suggesting solutions from, e.g., databases of previous cases.

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