Interaction of spatial and structural design, an automated approach

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This paper presents two procedures that are able to allow interaction between spatial design and structural design. 'Zone generation' and 'room positioning within structural constraints' both facilitate uni-directional interaction. Using these procedures consecutively yields an improved design method that provides interaction between spatial and structural design. A computer program in Prolog-2 has been developed for demonstration purposes. The method developed here can be applied flexibly because it is limited to only two procedures and there is the added advantage that the procedures can easily be extended or redefined.

Keywords: automated design, spatial design, structural design, design knowledge

Almost all research projects in the field of architecture are focussed on either spatial or structural design. Usually when spatial design and structural design are investigated in combination, only data models emerge (Khemlani et al., 1998). The authors believe that direct interaction between spatial and structural design will improve design quality. This article presents two procedures that will each facilitate one direction in an interaction process. Using both consecutively leads to a design method that provides interaction between spatial and structural design. This concept is presented in Section 1. Section 2 briefly discusses earlier published relevant studies and positions this study in the current field of research. Practical design examples are shown in Section 3. A small prototype program that demonstrates the method is presented in Section 4 including development and algorithms. Section 5 gives conclusions and recommendations for further research.

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1 Concept

A case study was carried out in which spatial and structural designs were investigated for a limited number of buildings. One specific concept emerged every time: within the confines of the spatial design, the structural designer looks for geometric volumes for which he knows structural solutions. The process in opposite direction was less frequently observed: if the architect wants to use a specific structural system, he rearranges the spatial system to fit the structure.

Figure 1 shows the interaction process schematically. A structural designer transforms a spatial design into a structural design: from top left corner to top right corner. The structural system can be improved by optimisation methods or expert views of other structural designers: from top right corner to bottom right corner. In this case two structural knowledge items have been used: (1) centre supports for beams are omitted, and (2) simply supported beams can be extended by cantilevers. The adjusted structural system allows the architect a new spatial design: from bottom right to bottom left. This spatial form can be transformed or altered again by the architect: from bottom left to top left. This design cycle can be repeated clockwise or anticlockwise several times and is defined as interaction of spatial and structural design.

It can be stated that a spatial design must have properties that can lead to a structural design, and vice versa, the structural system must possess properties that allow a spatial design. The authors believe that building

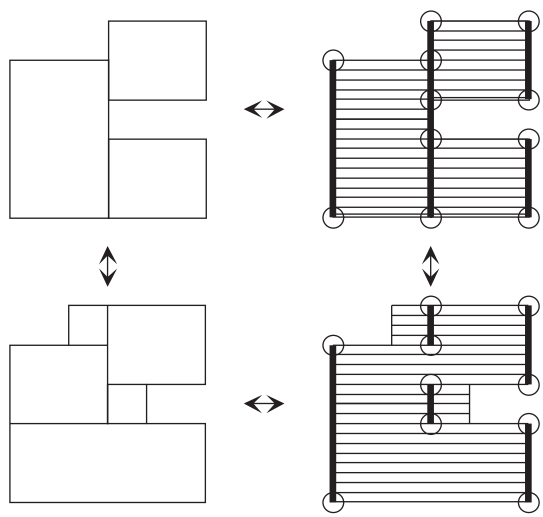

Figure 1 Interaction of spatial and structural design

designs are the most elegant and economic if designers are aware of these principles and use them.

2 Research position

Little has been published in the academic literature on interaction of spatial design and structural design. Salvadori and Heller's book (1986) 'Structure in Architecture' helps architects to understand structures. It treats aesthetics and structural correctness, scale and structural message, etc. but no extension is made to include interaction. An earlier publication by Schodek (1980) is indispensable from a structural point of view, although it should be noted here that spatial form follows structure.

In the field of computer-integrated building design, Fenves et al. (1994) study the design process by managing small computer programs, so-called 'agents' that are classified into 'generators' and 'critics'. The generators develop the design whereas critics evaluate the current design and make redesign recommendations. Spatial design and structural design are both present among the generators, whereas the structural design only employs critics, i.e. an interface program towards a finite element program. The work of Fenves et al. has two drawbacks: First of all, 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. Secondly, the monograph only presents ideas and not working programs, thus the validity of the ideas cannot be verified.

Academic research can be categorised into three important groups: automated structural design, automated spatial design, and combined structural-and-spatial design. Two other and more general groups are design knowledge and data models (see Table 1).

Automated structural design is defined here as the automation of all necessary tasks to design a building structure. Designing a building structure normally involves the application of a structural system, in cooperation with the architect, in addition to analysis and design of all structural parts (stress-engineering). Shea and Cagan (1999) show that the method of 'shape annealing' (shape grammars with stochastic search) is able to generate useful roof truss designs. Kim et al. (2002) show that using a finite element program, the optimum geometry of a structural element can be obtained as a function of the applied load and the variable selected for optimisation. Additional relevant research within the scope of this article was done by Sacks et al. (2000) who

Table 1 Current research

Groups	Types
Automated structural design	Conceptual structural design Sheap annealing (Shea and Cagan, 1999) Structural optimisation (Hofmeyer, 1995; Kim et al., 2002) Parametric templates (Sacks et al., 2000) Intelligent agents (Anumba et al., 2002)
Automated spatial design (Ligget, 2000)	Quadratic assignment problem Graph theoretic approaches Expert systems (Arvin and House, 2002) Shape grammars (Smyth and Edmonds, 2000; Wang and Pinto Duarte, 2002)
Automated structural and spatial design (Khemlani et al., 1998; Haymaker et al., 2000)	
Design knowledge (Meniru et al., 2003)	
Data models	Model architecture (Khemlani et al., 1998; Tolman, 1999) Model management (Chien and Flemming, 2002)

developed a system that is able to generate a structural design for rectangular one-storey buildings. It is based on 'intelligent parametric templates' which is described as 'a collection of object definitions, rules, and methods, which fully describe a set of building elements and define the ways in which they can be inserted into a building model'. Anumba et al. (2002) presented an automated procedure that combines a structural agent, an architectural agent (although not for aesthetical items but for building height constraints, etc.), and a design code agent which allows the design of portal frames.

Automated spatial design is the automatic grouping, sizing, and positioning of spatial elements, e.g. the design of a floor plan for a dwelling unit. Ligget (2000) presents an overview of research on automated spatial design. Research on spatial design used to be mainly focussed on one-storey buildings. Since 1988 investigations in this area have been extended to multi-storey design as well, however, with the restriction that the building more or less consists of equal storeys. Recent research on spatial design includes a study by Arvin and House (2002) that employs physical laws to group or arrange spatial forms. Wang and Pinto Duarte (2002) suggest the use of shape grammars – rules that define how spatial forms can be related and positioned (Smyth and Edmonds, 2000) – to generate three-dimensional designs of small buildings.

In automated structural-and-spatial design, Khemlani et al. (1998) investigated how a data model representing a building can be made intelligent in such a way that it is an useful aid in a schematic building design process. In this representation both spatial and structural aspects are taken into account. Haymaker et al. (2000) propose a procedure called 'filter mediated design'. For every design discipline, the meaning of a building component is specifically defined. One can think of a column as a visual vertical element for the architect and a load transfer element for the structural designer. Using the different meanings, their work produces buildings that are designed by several disciplines.

To automate the total building design process, which is much more than only a structural and a spatial design, knowledge has to be generated on the building design process itself. Meniru et al. (2003) published questions and reasoning by principals and designers that are necessary for making an actual building design. Their research suggests that the interaction method as developed by the authors, although simple and subject to refinement, is quite suitable for improving the design process.

For the design of automated design systems and the structured definition of knowledge, data product models are important. Tolman (1999) gives an overview of the history and future of building product models. These can be used to facilitate the building design process as shown by Chien and Flemming (2002). They developed a method to navigate through information and use a spatial design system to demonstrate its effectiveness.

It can be concluded that specific studies on interaction of spatial and structural design have not been forthcoming. The main focus has been on spatial and structural effects on the total building design process.

3 Knowledge on the relationship between spatial and structural design

Learning about the processes of spatial and structural design is possible by interviewing structural designers and architects, by studying building designs, and by browsing through the literature (Buettner and Hampe, 1976; Schodek, 1980; Salvadori and Heller, 1986; Ambrose, 1988). Case studies (Hofmeyer, 1994) on an office building in The Hague and an industrial building and a home care centre in Eindhoven will demonstrate the first two strategies.

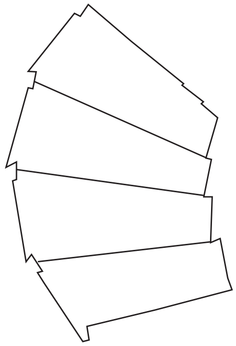

Figure 2 Office building with 25 levels, The Hague, The Netherlands

For each building, the structural design based on spatial design is shown in Figures 2, 3 and 4, respectively. The office and industrial building show that economic and/or aesthetic reasons determine which type of structure is selected for a given spatial design. The spatial design of the home care centre was made by the architect without consulting the structural designer. In the three storey spatial design, the roof level has a reduced width (see Figure 4). In order to adapt a structure to this design, a concrete skeleton of beams and columns was suggested as shown in the cross-section of Figure 4. The length of the main girders in the central bay is larger than the distance between the two interior columns. The beams in the exterior bays are supported by exterior columns and cantilevers of the interior bay girder. The girders and columns of the interior bay form a three storey portal frame. At the third level, the exterior bay beams and columns have simply been left out, thereby creating a reduced level width.

The three case studies showed that designers are often not explicitly aware that they can follow an interaction design sequence as shown in Section 1. A discussion on the need for interaction between spatial and structural design in practice can be found in Hofmeyer et al. (2005).

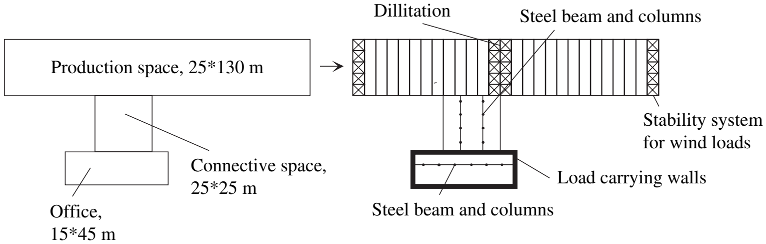

Figure 3 Industrial building, Eindhoven, The Netherlands

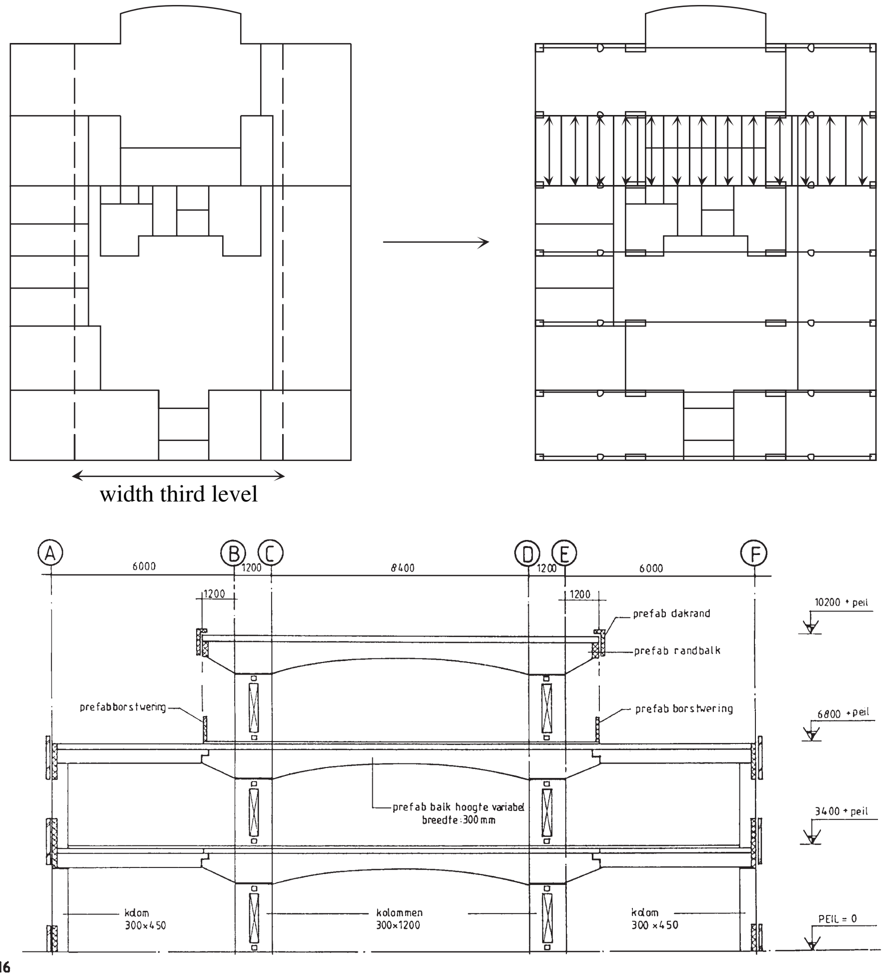

Figure 4 Home care centre, Eindhoven, The Netherlands

4 Prototype program

In Sections 2 and 3, it was shown that neither current research on design automation nor building design practice consciously studies or uses the interaction of spatial and structural design. To initiate this, a prototype computer program was developed. The program features two important procedures: (1) *zone generation* and (2) *positioning rooms with spatial constraints*.

4.1 Development

For the computer program, requirements, actions and definitions are developed (Walker et al., 1990) based on the concept presented in Section 1. This leads to a program that for a limited number of rooms with given dimensions is able to present several structural systems with approximate dimensions for the individual structural elements. Subsequently, the structural design is followed by spatial design. The computer program serves the complete design process. For demonstration purposes the steps in the design process are limited. The program requirements for development are as follows:

1. In order to develop a preliminary structural system, it will be necessary to have an initial spatial design. The translation from user input (e.g. rooms, dimensions, constraints) to a spatial design is therefore first carried out by the program.
2. The development of a structural system with element dimensions is restricted to a limited number of different types of structural systems and types of elements.
3. The effects of the interaction between spatial-and-structural design and feedback from preceding design steps are taken into account by making the spatial design subject to the structural design, i.e. form follows structure.
4. Evaluation of every design step and adjustment of the design must be taken into account.

With the above requirements, the actions and definitions of the program can be specified. Detailed structural phenomena like stability, lateral wind loads and earthquake can be taken into account but are not used here to provide a clear view on the idea of interaction. The program definitions and actions are as follows:

Program definitions

- A building structure comprises storeys.
- The building foundation is assumed to have infinite stiffness.
- At all levels rooms are already present or can be introduced.
- Rooms are rectangular with specified surface dimensions.
- A zone is a group of rooms at a single level with a rectangular boundary.
- A level may comprise any number of zones.
- The structural elements may consist of steel or timber beams and columns, concrete columns, walls and floor elements, and steel space frames and sheeting.
- The structural systems for each zone only provide vertical load bearing elements and upper floors subjected to gravity loading. They may consist of the following: (1) timber beams and columns connected to form portal frames, (2) steel portal frames consisting of columns and beams supporting steel sheeting, (3) concrete walls supporting concrete slab elements, or (4) concrete columns supporting a steel space frame.

Program actions

- The rooms are positioned on one level at the time. If the storey below already has been assigned a structural system, the positioning of rooms is adjusted to fit that structural system. All possibilities will be generated.
- At a specific level all possible zones are generated within the constraints of the previous action.
- For the generated zones, all possible structural systems are determined for all possibilities allowed by the previous action. This is done by making use of so-called shape grammars, i.e. for each zone shape there exist a limited number of structural systems (Shea and Cagan, 1999).
- Rooms are placed and located on the adjacent level above; zones are generated and provided with a structural design, etc.

The selected approach of definitions and actions can easily be combined with existing space-allocation techniques (Smyth and Edmonds, 2000; Arvin and House, 2002; Wang and Pinto Duarte, 2002). Zone generation is a useful first step in generating procedures for structural systems. It relates to the structural engineer's intuitive action to make a structural design for groups of spaces.

4.2 Algorithms

This section presents the four algorithms of the computer program: (1) spatial design, (2) zone generation, (3) structural design, and (4) positioning rooms within structural constraints. The main structure of the program is shown in Figure 5.

4.2.1 Spatial design

A simple space-allocation technique will be used for an initial spatial design. A rectangular room is positioned on level x with a $1 \times 1\ m^2$ grid. Room dimensions are rounded off to 1 m. The middle of the room is used as a reference point for its location. Subsequently, the next room is positioned, such that the input constraints are satisfied. This process is continued until all rooms on this level are positioned. The spatial design is programmed declaratively: it is only stated that a room should be positioned within the constraints so that valid solutions can be generated.

4.2.2 Zone generation

Zone generation tries to describe the working method of a structural designer. The principle behind zone generation is that in each spatial form,

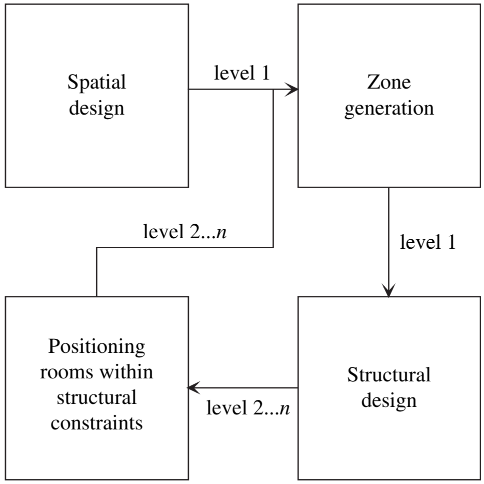

Figure 5 Program main structure

patterns can be recognized that allow the structural engineer to design a structural system. The algorithm functions by generating a set of all corner locations of all rooms on a single level. The set of locations can be used to generate rectangles from existing corner locations. A set of declarative rules takes care of finding all possible rectangles. A rectangle selection must be carried out because many rectangles exist that are not zones, e.g. the total boundary of the zone is not fully occupied by rooms. Finally, rooms must be grouped into a single or multiple zones (see Figure 6). Each room can only be part of a single zone. A set of declarative rules takes care of making all possible zones for all possible spatial designs. The end product of this algorithm is a series of spatial designs that consist of zones.

4.2.3 Structural design

The process of assigning structural systems to zones is dependent on the zone dimensions. The generated structures may span a zone consisting

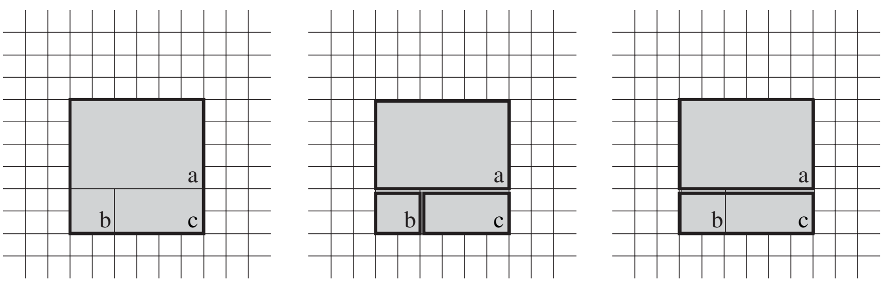

Figure 6 Zone generation, zones are indicated by bold lines

of just a single room or a profusion of rooms. There are four structural possibilities available: (1) timber beams and columns forming portal frames, (2) steel portal frames supporting steel sheeting, (3) concrete walls carrying concrete slab elements, and (4) concrete columns supporting a rectangular steel space frame. Approximate dimensions of the structural elements are obtained from basic preliminary structural design rules. Furthermore, grid lines and the weights of steel and concrete structures are determined for evaluating the design. The declarative rules assure that every possible structural design is generated.

4.2.4 Positioning rooms within structural constraints

The positioning of rooms within structural constraints tries to relate spatial design to structural design. The rooms must be positioned such that the structure to be developed for these rooms will fit the already designed structure underneath. The first step is to position a room in a similar a way as for algorithm 'spatial design'. Besides the prescribed relations between rooms, additional constraints are now introduced by the structural system underneath (see Figure 7). A room placed on a level will be checked for possible overlaps with and adjacency to existing rooms. If there is interference between rooms or the new room is not adjacent to an existing room, it must be relocated; otherwise the program can continue with an additional room. When this process is complete, zone generation and structural design are applied to the relevant storey. If there are more levels, spatial design within structural

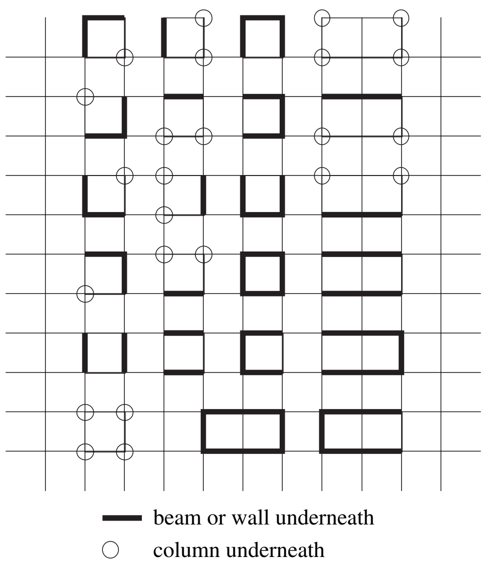

Figure 7 Constrained positioning of rooms

constraints, zone generation, and structural design are applied again (see Figure 5).

4.3 The computer program

The computer program, in Prolog-2 for Windows (ESI, 1994) declarative language, implements the procedures of room positioning and zone generation within structural constraints. In a declarative language, facts and rules are defined first before the program gives solutions; this is opposite to a procedural language where a number of steps must be described to solve a problem. In general, declarative programs are well suited for solving artificial intelligence problems (Walker et al., 1990).

Although advanced methods are available to facilitate the input of spatial information (Ligget, 2000), for demonstration purposes the data input for rooms, spatial constraints and storey level information are carried out in a text-box. The program generates floor plans and the user opts for further processing or allows the program to design a new floor plan. The designer is also able to change the floor layout by moving rooms to new locations. The program will generate new zones for all floor plans. Then for each 'zoned' floor plan an adjusted structural design is created (see Figure 8). The program also gives information on weight of structural steel and concrete. The user can now decide to save or delete the structural system on display. After all possible structural systems have been shown, the spatial design moves to the next level where positioning of rooms within structural constraints and zone generation begins again.

5 Conclusions and further research

Recent literature shows research on structural design, automated structural design, automated spatial design, design knowledge, and the development of data models. Little is presented on automation of interaction of conceptual spatial and structural design. Also for practice, case studies show the limited conscious use of interaction. However, interaction should be taken into account explicitly for further progress in automation research (Hofmeyer et al., 2005).

Simple procedures have been suggested for zone generation and positioning rooms within structural constraints. Using these procedures consecutively yields an improved design method that provides interaction between spatial and structural design. The procedures should not be regarded as a complete design method but represent a germ of an

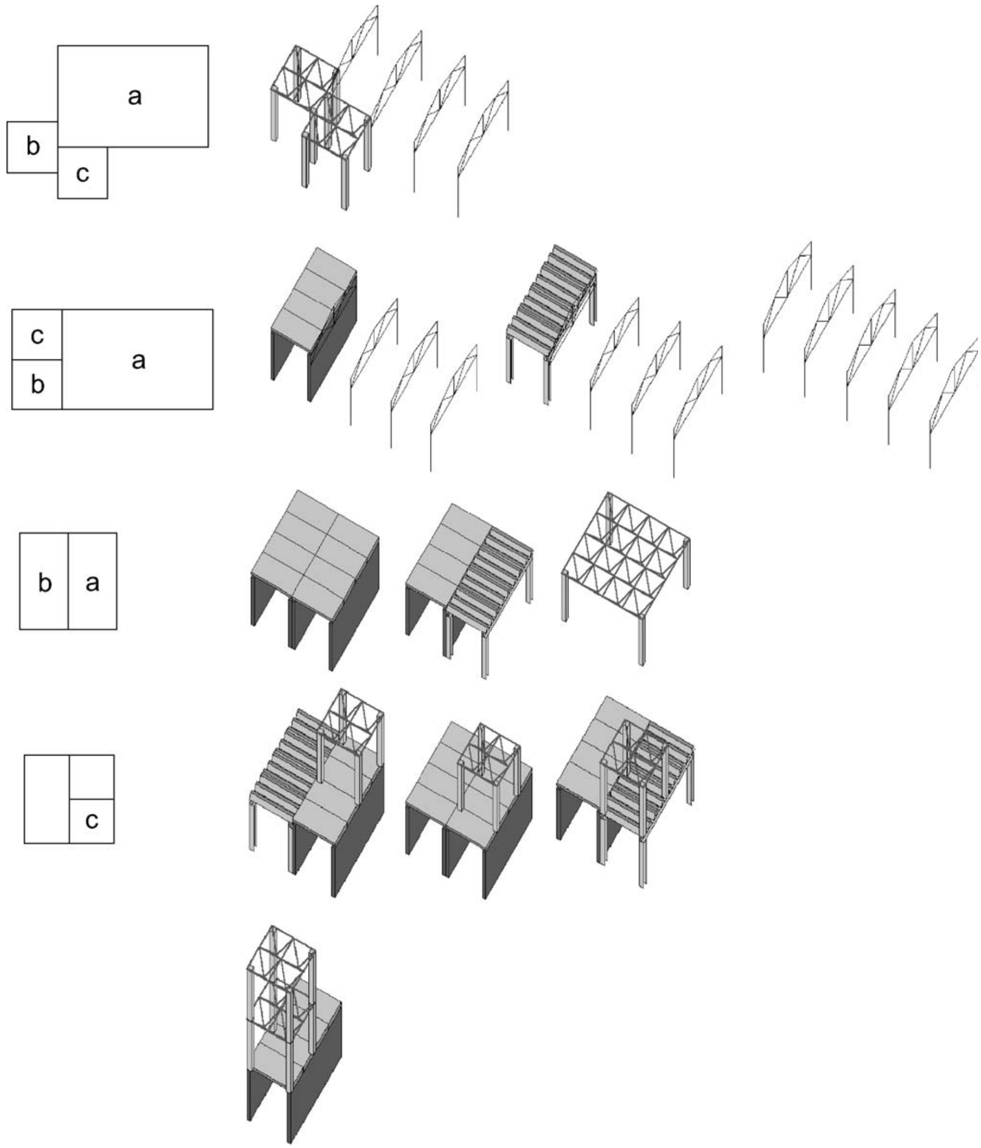

Figure 8 First two lines: three room designs, one spatial design with one structure, one with three structures. Third line: two room design, three structural designs. Fourth line: two level design, three structures. Last line: three level design

idea: to include with the layout of space also the layout of basic structure.

A Prolog-2 program demonstrates the application of the two proposed procedures. 'Zone generation' is performed per building storey and thus represents a horizontal two-dimensional procedure. Similarly 'room

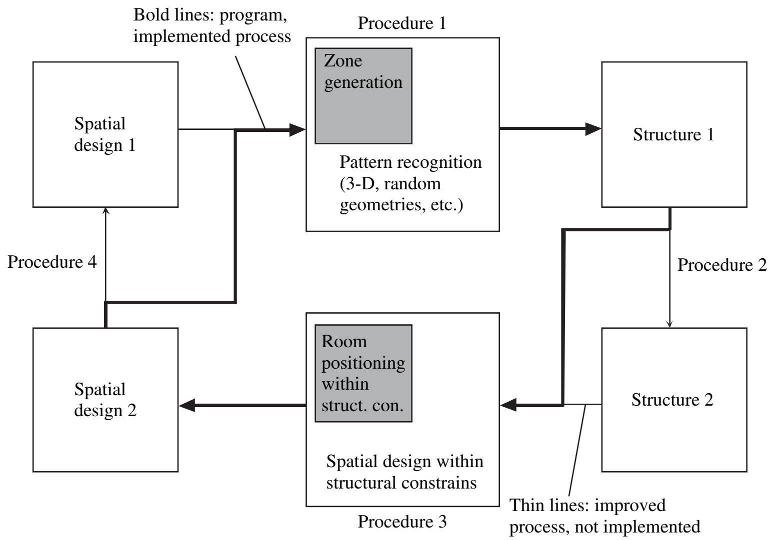

Figure 9 Research presented (grey) is a part of research to be carried out (white)

positioning within structural constraints' is a planar vertical operation. These two features are represented by procedures 1 and 3, which make part of a more complete design method shown in Figure 9.

The program at this stage is not able to optimize the structural designs or spatial designs as indicated by procedures 2 and 4 in Figure 9.

Improving the interactive design method would require future research to include procedures 2 and 4 and to focus on full three-dimensional zone generation and room positioning (Figure 9). For procedure 2, an example of the optimisation of a small three-dimensional structure can be found in Hofmeyer (1995). The method allows a wider application in, e.g. industrial, mechanical, and aeronautical design, where spatial and structural design processes are of equal importance.

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