MODELS AND PRODUCTION SYSTEMS FOR MULTIDISCIPLINARY OPTIMIZATION IN BUILDING DESIGN

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ABSTRACT

This research project deals with a method for transforming a building design into a parameter-based optimization model considering the specific constraints as well as typical ways of the realization in building construction. In contrast to many conventional approaches of structural optimization, this project aims not at minimizing the weight of a single element but at enhancing the multidisciplinary performance of the whole design. In the first part, a hierarchical structure of components for establishing a system-oriented model is proposed. On the one hand, the components serve to manage constraints from architecture and other disciplines. On the other, they are supposed to represent the common methods of construction. Furthermore, the arrangement of the components is also a relevant possibility for improving a building design, especially, in early design phases. Therefore, the second part deals with groups of components with variable quantity of members and grammar-based modifications of the system established by the components. Rules define how to add, remove or exchange components. The decomposition and the system modifications will be illustrated by an architectural example.

KEYWORDS

Multidisciplinary Design Optimization, Decomposition, Optimization Model, Production Systems, Shape Grammar

INTRODUCTION: DESIGN OPTIMIZATION FOR BUILDINGS

The process of designing buildings consists in searching for a good solution. The designer has to integrate the various demands imposed by the involved disciplines into a system of interacting elements. Usually, he or she does this step-by-step – a time-consuming process. Furthermore, the design is supposed to perform well in terms of costs, resources and construction time. This raises the question why computer-aided optimization is hardly ever applied in building design as a supporting tool in this search.

Therefore, my research project deals with the possibilities of applying optimization in designing building constructions. Since it is a running research project, I aim to point out and discuss important aspects in order to outline the approach and provide a framework, which will be detailed in the further progress of the project.

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The techniques of mathematical and computational optimization have been developed to a large extent. Many different methods provide means for optimization in various situations. In contrast, the optimization models do not sufficiently consider the specific characteristics of building design. Usually, conventional structural optimization considers the amount of material and the stiffness of the construction. As discussed in a previous paper (Geyer and Rueckert 2005), these objectives do not meet the needs of building design since there are other relevant aspects like construction and maintenance costs, required resources, function, aesthetics, and spatial qualities for example. Especially, the last three aspects are essential for architecture. For maintaining the architectural idea, the consideration of these aspects during a numerical optimization process is required. This causes a problem since they are partly of non-numerical nature.

In this context, the decomposition of the design into a system of parametric-linked components is of major importance since it enables the designer to consider these aspects as constraints. An essential part of the architectural design consists in the type of chosen components and their arrangement. Therefore, in this contribution a structure of components is proposed enabling an optimization model to include the architectural design as well as the possibilities for optimization. On the one hand, components are typical elements, like walls, columns, floor slabs, openings, and so on, which serve to describe an architectural design. On the other hand, components are also structural elements like girders, trusses and columns as wells as cross sections and materials. The components represent the appearance or the usual methods of construction and connect these aspects with financial efforts, resource amounts, and construction times. Furthermore, for optimization the components will be equipped with parameters and analyses. These components shall serve to bring non-numerical aspects as constraints into numerical optimization.

The parameters, which the components comprise, provide one possibility for optimization. Furthermore, an essential potential consists in the arrangement of the components, primarily the constructional ones. Therefore, the second part deals with exemplary grammatical rules for modifying the system of components. By the formulation of such modification rules, the solution space, which the optimization algorithm is able to examine, is largely extended.

NON-NUMERICAL ASPECTS AND IMPLICIT CONSTRAINTS

Before starting with the components, the nature of the non-numerical aspects and their implementation as constraints need to be examined. As mentioned above, these aspects cannot serve as criteria in a numerical optimization process. It is difficult to express them adequately in figures and evaluate them with an algorithm since the assessment of these aspects requires constructional experience, an artistic sense, or a social discernment. Furthermore, the designer mostly has a better ability to handle these aspects. This suggests handling them as constraints for the numerical optimization.

First, constraints are bounds restricting the range of a design variable by defining a permissible interval. This type of constraint is explicitly expressed by numbers. The other type, which I call implicit, is usually not mentioned in the context of constraint. However, the implicit one is a restriction at least as strong as the explicit one. It arises from the internal structure and the formulation of the optimization model itself. The way of describing the design and the choice of variables being subjected to optimization sets the limits for the space of possible solutions to a high degree. The optimization cannot yield a solution that is not provided by the model. These model inherent restrictions are of very much interest because in contrast to the explicit ones they cover non-numerical information. The establishing of the model includes them in the optimization process. During the conversion of the design idea into an optimization model, a process I call decomposition[2], these constraints are defined. Thus, I intend to include the non-numerical aspects of building design by means of the decomposition with specific components in the numerical optimization. The selection, the arrangement, and the linking of these components cover non-numerical information.

Some of the required components exist. The second generation of computer-aided architectural design (CAAD) uses a semantically rich representation of data. For instance, the Industry Foundation Classes (IFC) enable the representation of a building design in a standardized way with specific components. Approaches like Fenves and Rivard (2000) presented related schemes intended for the conceptional design of load-bearing structures. These approaches are used as a basis for the component structure in my project. For the existent components, parameter interfaces are necessary. In other cases, for example for the grouping, new components are required.

DECOMPOSITION

Building design largely works with standardized elements: The architect forms the design with walls, floor slabs, openings, beams, columns and so on. The arrangement of these elements constitutes the design and defines rooms and spaces with certain qualities. At every stage, an architectural or constructional model results, which embodies the current state of the design or one possible variant. In contrast, the optimization model does not represent only one solution but a large number of different solutions. To achieve this, the designer is required to describe the possibilities for changing and the constant circumstances in the design, which shall be maintained. For this purpose, parameter optimization introduces design variables and constraints. In the component-based approach, this means to arrange and to connect the elements as well as to choose free, not linked, variables as design variables. This establishes a system that describes possibilities of changing the design, keeping track of the consequences for the whole system.

COMPONENT DERIVATION AND FUNCTION

A functional concept serves to define the components. In the system, each component fulfills its function. For instance, a simple beam serves to transfer linear or single loads on a line to the two locations of the bearings. This implies first a geometrical relocation and second the conversion from linear forces to single forces. This notion of function is related to that proposed by Mitchell (1991) for structural elements. In an architectural context, the function of a wall for example is the separation of rooms. This is first visual but with respect to the

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[2] The term decomposition is used differently from its normal usage. In optimization, it originated in the partitioning of the problem into coupled subordinate problems to decrease the computational costs. However, in a system which naturally consists of components, the boundaries of decomposition likely coincide with the component interfaces.

other involved disciplines like building acoustics, climate or fire protection, this functional characteristic leads to technological constraints with which optimization has to comply.

This top-down approach keeps the latter constructional realization open and provides in this way an additional possibility for optimization besides parameter variation. Especially for the exchange of components, the second part deals with, the functional approach is of high importance.

In the scheme of a hierarchical system like that shown in Figure 1 for a floor slab, a component receives functional requirements from the superior component and imposes other functional requirements to subordinate components. The elements in the first row represent the function in a more abstract way than those in the second row. The floor slab distributes its requirements to its constituent parts in the next step of realization.[3] The insulation for instance meets the floor slabs need for acoustic or thermal separation by the floor slab, or the metal sheet and the beams provide the load transfer from the floor area to its edge.

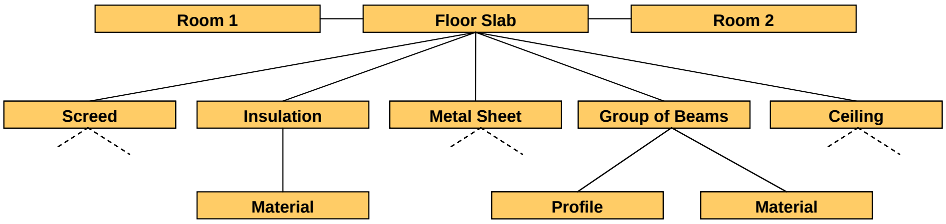

Figure 1: Functional hierarchical structure of the components.

An example, used for illustration in the following parts of the paper, contains the floor slab. The example represents a part of a sports hall containing a foyer on the first floor and a room for gymnastics on the second floor. A rendering of this part of the building is shown in Figure 2. The architectural idea consists in a "hovering" cube and a structure, which is as transparent as possible, to support the cube.

Figure 2: Desired appearance of the architectural design for the entrance foyer and the small hall on top.

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[3] This is a specific nature of modern constructional solutions. In more traditional ways of construction, the function is fulfilled by a few components or a unique component.

COMPONENTS AND CONSTRAINTS

The elements that serve to describe an architectural design constitute one important group. The main component in this context is the indoor room. The utilization sets its area and height. The architectural idea generates an arrangement and adds further elements like walls, floor slabs, façades, and so on. From a functional viewpoint, these elements all serve to separate rooms. For completeness, one special object is introduced: the outdoor space. Figure 4a shows this for the entrance building with a small hall above.

This description first imposes geometrical limitations. The height of the rooms and that of the building itself determine the limit of the space for the other building parts. Considerations regarding the proportion of the two bodies, the hovering cube and the transparent base refine these constraints (as shown in Figures 3b and c). In the design example, these conditions cause constraints for the constructional height of the roof and the floor slab. These constraints will cause more materials-intensive and expensive construction than without them.

Furthermore, the architectural design aims to have no diagonals either in the base or in the cube above (Figure 3c). This leads to a constraint that is, in contrast to the previous ones, non-numerical. The wall and the façade element contain this condition as a feature. Either the designer chooses one structural component at the outset which meets this requirement, for example a rigid-frame girder, or, if the constructional type of the component is subjected to optimization, the rules of changes and the evaluation have to exclude unsuitable components like a lattice girder with diagonals.

In view of the other disciplines involved, the architectural prerequisites lead to constraints of a more technological nature. In connection with the architectural design, specific laws, standards, and rules, as well as considerations towards the comfort, impose these constraints. Regarding the building parts, there are requirements for insulation and fire resistance for separating the rooms (Figure 4). The construction chosen for realization of the building parts has to comply with these constraints.

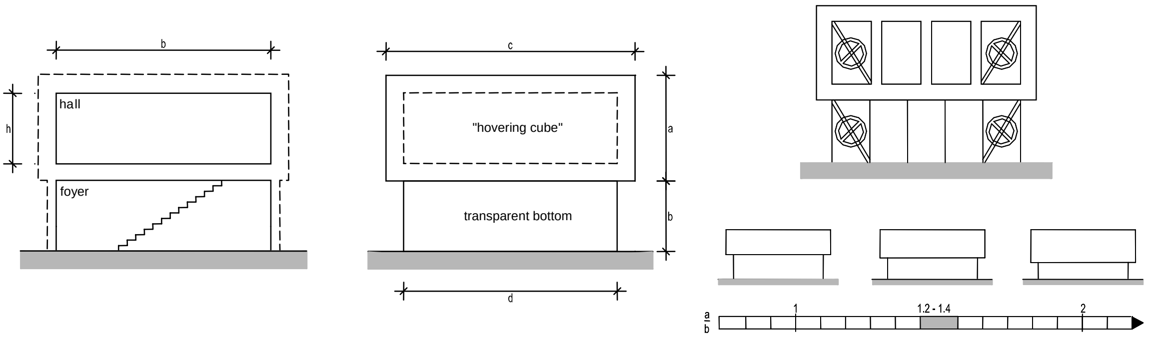

Figure 3: Architectural constraints: a) the use, b) the outward appearance,
c) the proportion of the bodies and the requirement for no diagonals in the façades.

Furthermore, the climate characteristics, for example, do not only concern the constraints but also the objectives for optimization since they affect the energy consumption and, as a result, the resource balance and the operating costs. For this purpose, the model also has to consider the required airflow rate, which is linked to the overall volume of the building and to the radiation passing through the façade. This links the climate to the geometry and closes the circle of interdisciplinary feedback. Therefore, a multidisciplinary approach is required.

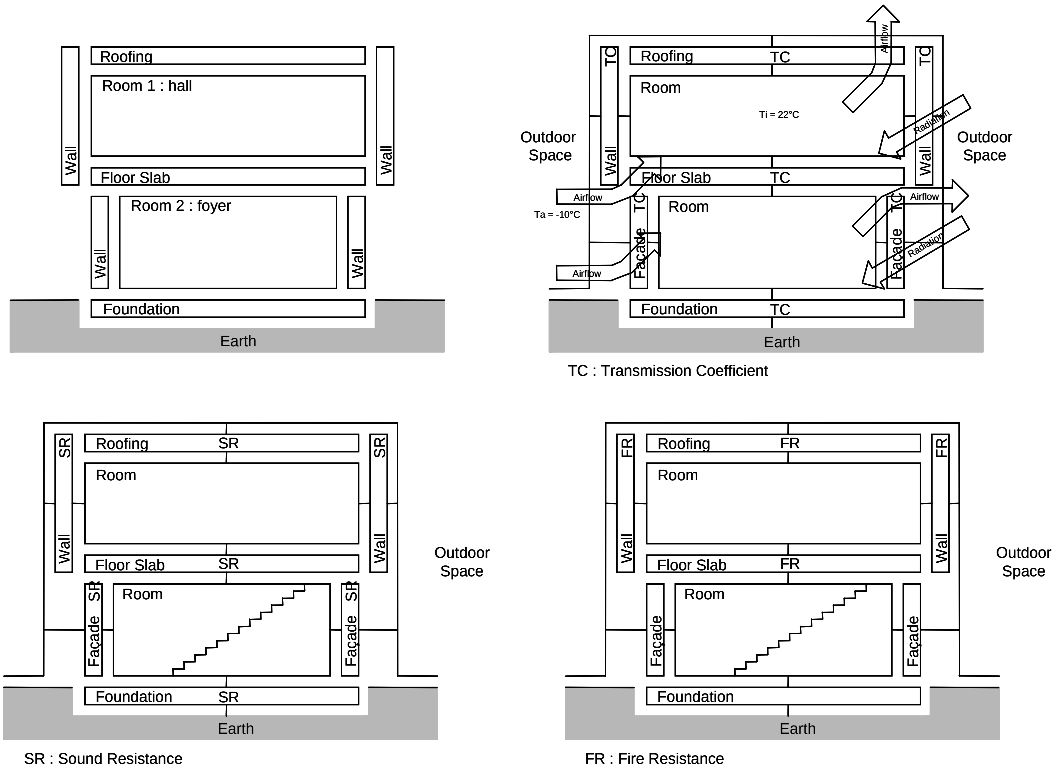

Figure 4: Models for different disciplines: a) architecture, b) indoor climate, c) building acoustics, and d) fire protection.

STRUCTURAL AND CONSTRUCTIONAL COMPONENTS

So far neither materials nor construction has been considered in the model. However, both are required for obtaining the values which describe the performance of the design, such as the amount of material or the quantity of parts. Although it is not necessary to know every detail for optimization, it is required to know how the construction works in regard to the different disciplines and whether a connection of two components is feasible or not. Only in this way does the dimensioning become possible. To provide this constructional information is the purpose of the second domain of components.

The first step towards constructional design is the assignment of the load transmission path (Figure 5a). In the example, the roof is defined as a two-way slab, whereas the floor slab is defined as a one-way slab, which meets the requirements of the opening for the stairs. By this step, a draft of the structural system and the functions of the elements in terms of load transfer are defined. In the next step, a steel girder construction or steel grillage is assigned to the slabs. In order to vary and to improve the solution, the designer or the algorithm might, for instance, assign a concrete construction to the slabs. The steel construction requires a second subordinate group of structural components that consists of the beams. These components are part of the structural system since they also achieve a load transfer.

In the structural stage, the quantities transferred between the components consist mainly of different kinds of loads, such as area, linear or single loads, in connection with the geometry. This transfer reflects the function of the components. Thus, the structure of the parameters determines the possible functional range of a component. The function-oriented definition provides the basis for the exchange of components discussed in the system modification section.

At the next level, the detailing of the components with materials and sections takes place. The internal forces and bending moments of the structural components are transferred to these subordinate ones. For determining the performance in terms of costs and materials, it is necessary to descend to this level of detail since it is here that the quantity of parts or joints, the dimension, and the amount of material are figured out. The dimensioning for stresses takes place at this level and the proof of stability and serviceability is done in conjunction with the above level.

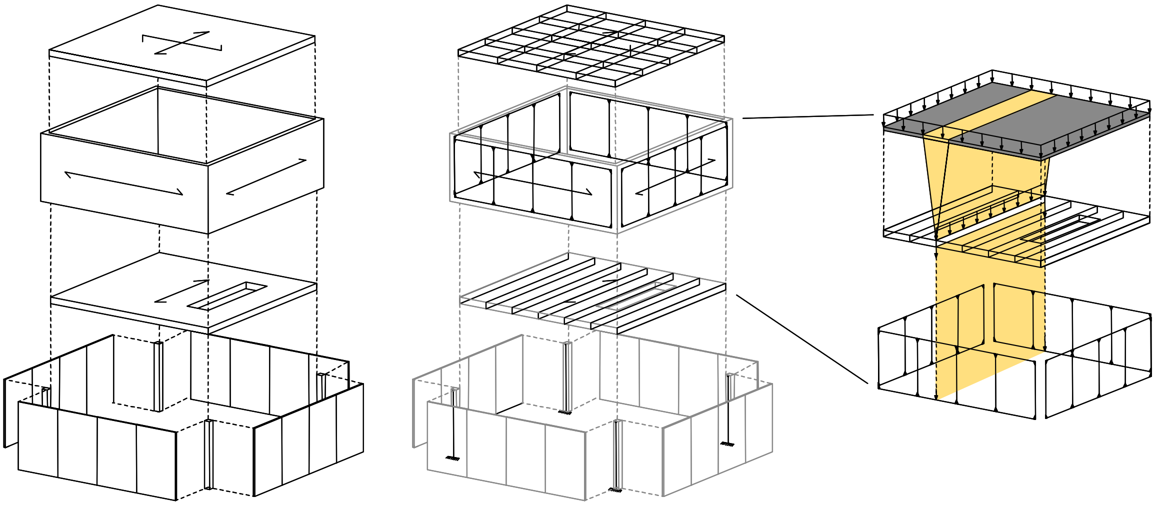

Figure 5: Three-dimensional structure of the load-bearing system, a) draft of the system, b) constructional realization and c) the load transfer path.

For the other disciplines, the dimensioning is simpler since the geometric laws are not so complicated and the function consists, for the most part, in the separation. The insulation layer for the climate, for instance, is defined by the design variable thickness and the subordinate component material with its thermal characteristics. Both determine the thermal resistance of the component. The acoustic characteristics depend in a similar way on the mass and the surface of the component as well as the stiffness and the number of layers. Fire protection has two different aspects of analysis. First, it separates rooms and therefore the components require resistance. Second, the construction has to retain its bearing strength throughout the evacuation time. This connects fire protection to the structural design.

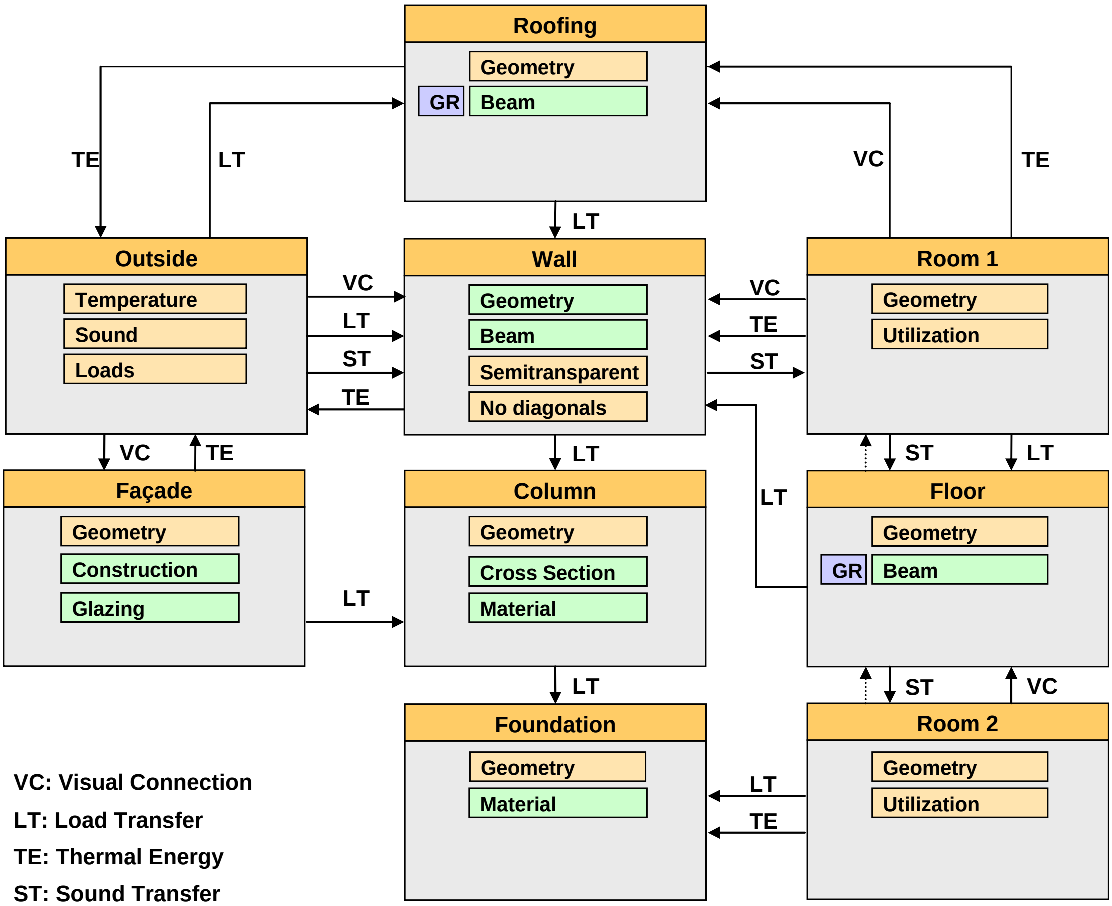

Figure 6: Overview of the decomposed system with its dependencies

DESIGN VARIABLES AND GROUPING

Now the model is organized in a component-based way with constraints and analyses. The components are established and linked in a system describing the design. Some of the parameters are linked to other components; others are predefined. Those that remain undefined and unlinked are available for optimization as design variables. An optimization algorithm changes them in order to obtain the best result in terms of performance.

In this context, the above-mentioned grouping of components is of major importance. It meets the usual procedures in planning and production since an element is designed only once and manufactured in quantity. The floor slab, for example, contains a group of girders of the same size (see Figure 7). Either the elements in the group sustain the same loads or the dimensioning follows the heaviest load combination.

However, by introducing a group component a new possibility for improving the design arises since the number of elements in the group can be adjusted. The group usually provides a range to bridge, which is either geometrical length or an angle in the case of circular designs (Figure 8). This characterization is usually a preset constraint, whereas the number and the distance of the elements is a design variable. This parameter may be changed according to the surrounding circumstances, such as openings with fixed positions, the covering slab's maximum span, or the sizes in which the elements are produced.

The grouping represents a transition from a static system of components towards a changeable one. It reflects the possibility of adding or removing elements in a row in accordance with a design variable. However, up till now, the system has not been modified.

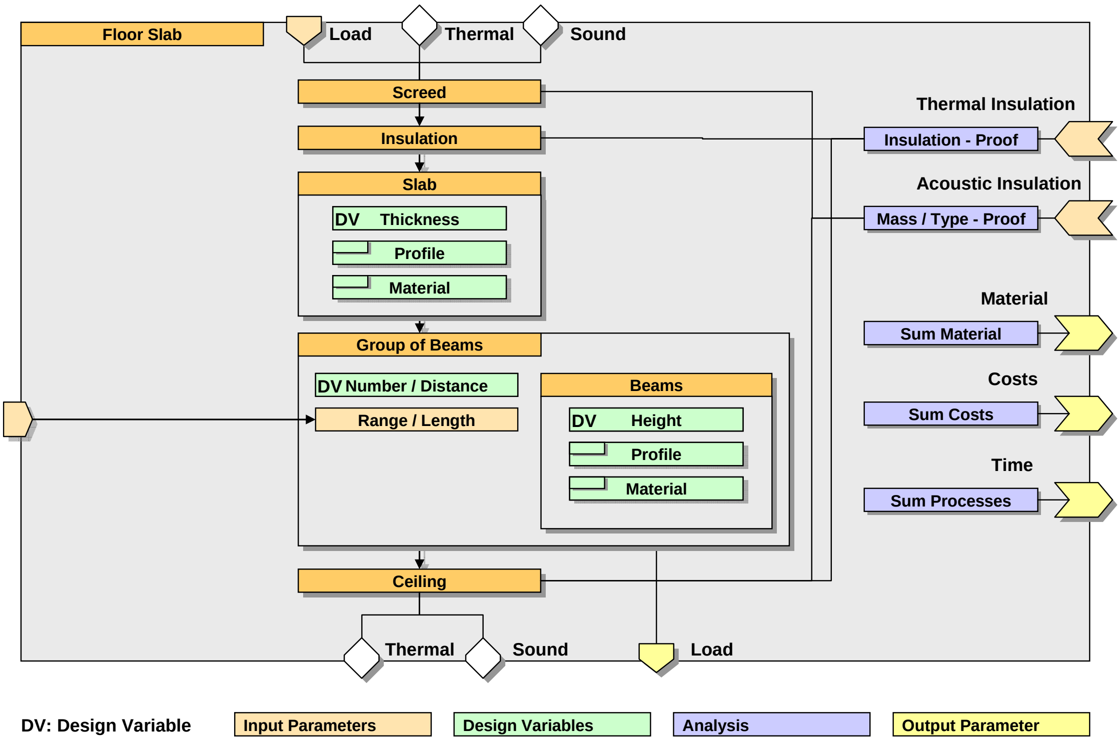

Figure 7: Structure of the floor slab with its subordinate components.

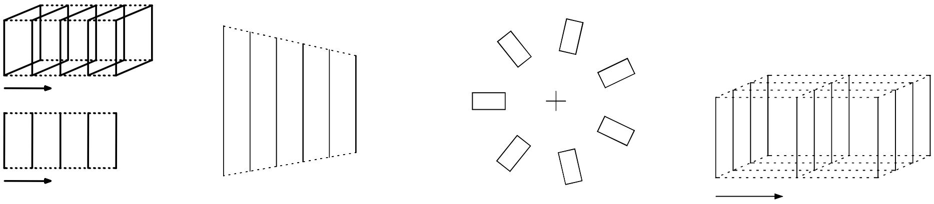

Figure 8: Types of groupings: a) series, b) tapered series, c) circular arrangement, and d) array.

SYSTEM MODIFICATIONS, GRAMMARS, AND PRODUCTION SYSTEMS

Besides parameter changing and varying the number of elements in a group, an important possibility for optimization is to change the arrangement of the parts. By context-sensitive rules describing the addition, the removal or the exchange optimization is able to perform system modifications. The Shape Grammar, for example, uses rules for developing architectural and geometrical designs (see Stiny and Gips 1980). Mitchell (1991) proposed a functional grammar, which serves to develop the design of a structural system step-by-step from a solid model. Recent projects in engineering design transferred this approach to the optimization of primarily mechanical designs, which are of less aesthetic interest (see Cagan 2001, Schmidt and Cagan 1998 and Shea and Cagan 1998). Constructional building design requires both domains: On the one hand, the appearance and aesthetics are of importance; on the other, the consideration of the technical design and the analysis is required.

Furthermore, the structures of building design are highly modular and the solutions are less predefined than that in other engineering design disciplines. The variety of forms and designs is much richer than, for example, in automotive design. Thus, in building design standard solutions in terms of configuration and layout hardly exist. Therefore, the modification of the arrangement of the components opens up a large and essential potential.

RULES FOR MODIFICATIONS

In the architectural example, the structural system of the base consists in fixed columns. Transformation rules introduce a frame and a greater number of supporting columns as shown in Figure 9 and 10. In the first rule, a frame replaces the joist and the two columns and adds two subordinate elements, the horizontal and the vertical element, to the system. This rule is applicable whenever fixed columns support a beam. By this action, the dimension of all involved parts will change, which might, of course, affect the performance as well as the appearance. The prerequisite for the application of the rules is that both configurations are able to fulfill the same function. In this case, the function consists of sustaining single or linear loads in vertical or lateral directions.

The second rule inserts a group component covering column and foundation. The application of this rule reduces the bending moments but increases the number of parts and connections in the structure. Furthermore, the number and the size of the façade elements now depend upon the load-bearing structure. This change affects even the appearance: instead of having strong profiles at the corners, the loads are distributed to several elements, which are more slender. Since the situation of the bearing for the joist is modified, its type changes to a multi-bay beam. For the façade, the construction also changes since it no longer needs its own beams between the ceiling and the floor.

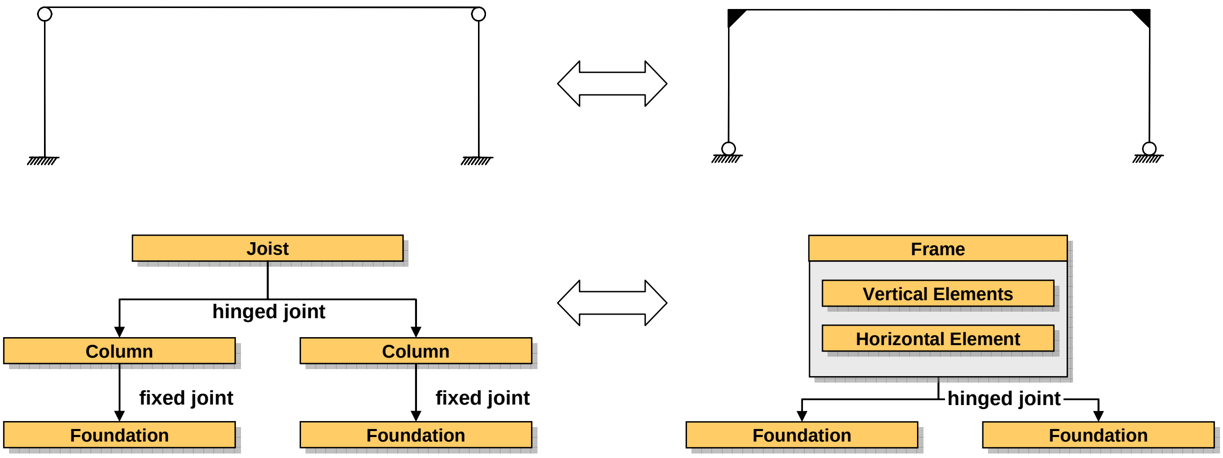

Figure 9: Transformation rule for exchanging the fixed columns for a frame.

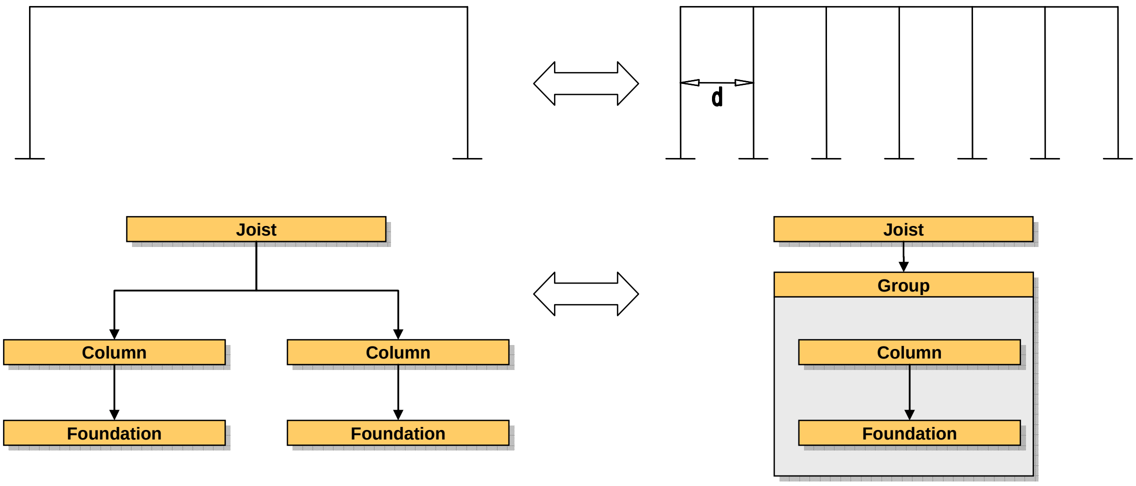

Figure 10: Transformation rule for inserting a group.

In a given design situation, the designer may select the rules manually, or the algorithm may apply them and proposes solutions from which the designer chooses one. This interactive approach is required because the rules may affect non-numerical aspects as mentioned above. The first two rules proposed do not lead to any contradictions with the constraining conditions of the architectural design. Figure 12 shows other rules that conflict with the no-diagonal constraint. To prevent the neglect of constraints there are two strategies: either to admit only those rules that will not cause violations of the constraints, or to identify and to eliminate the inadmissible or infeasible solutions during evaluation by applying penalties.

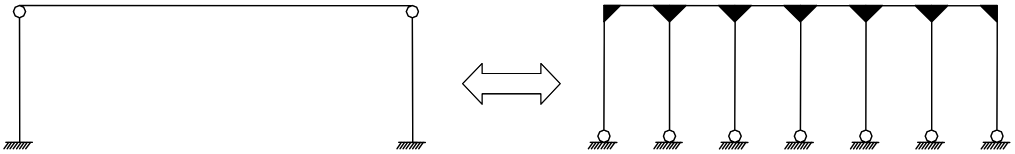

Figure 11: Possible transformation resulting from the rules

Figure 12: Rules contradicting the no-diagonal condition.

CONCLUSION

The paper illustrated a methodology to transform an architectural design into an optimization problem. A system of components is proposed serving for describing the design not as a static model but covering the possibilities for changes. This allows an algorithm to support a designer in figuring out a good solution by a systematical search. The components represent building parts, constructions, and materials with their non-numerical characteristics, the specific ways of construction, and their analyses in terms of required resources and costs. The component-based approach takes in account that the modification of the system is an important possibility for improving the system. A system of rules shall serve to improve designs in this respect.

The next steps of the research project comprise the detailing of the components and rules as well as the examination of the interaction between parameters and rules. Besides the definition of contexts, specific parameter values could serve to decide whether a rule is applicable or not. This enables engineering knowledge to be included into the optimization process.

The components serve as the basis for an interactive environment for design optimization that enables the engineer to get a better idea of the design and of the space of possible solutions. The whole system developed in the project is intended as a support for the designing engineer not as a replacement of him. The necessity of non-numerical assessment prohibits a complete automation of the process eliminating the designer by an optimization algorithm. Every solution proposed by the algorithm needs the revision by a qualified engineer.

The aim is to establish an optimization model that enables an algorithm to propose feasible and good alternatives in an interactive design process. In this context, the components serve to include the architectural design, make possible interactive operation, and represent common ways construction. Furthermore, they make it possible to cover the whole design with its internal dependencies. Therefore, the components provide the basis for an interactive and multidisciplinary design optimization for building design.

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