EMBEDDING OPTIMIZATION IN THE DESIGN PROCESS OF BUILDINGS – A HALL EXAMPLE

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ABSTRACT: Considering the economic effort and the ecologic impacts of the building industry, optimization embedded in the design process of buildings is desirable as a flexible tool. To apply Multidisciplinary Design Optimization (MDO) to building design, adaptations to the special needs of this field are required. In this paper, first, appropriate objectives are discussed, which distribute to three major groups: economic performance, ecologic performance, and preference accordance concerning aesthetics and functionality. Second, the decomposition by components specific for building-design, which link non-numerical qualities with physical, economic, and ecologic quantities, is discussed. The steps are illustrated by means of a demonstrational hall design. Finally, the results of a test run presented for this example reveal the nature of the design space. In conclusion, the specific objectives and components and the system-oriented decomposition provide the basis for a CAD-oriented usage of optimization during the design process.

KEYWORDS: multidisciplinary optimization, building-design-specific decomposition, optimization model, computer-aided design.

1 INTRODUCTION

Multidisciplinary Design Optimization (MDO) provides a powerful means to support the design process. However, it is rarely applied to building design. Therefore, the research presented in this paper deals with setting up an optimization model suitable for this domain and compatible with the already developed techniques of MDO.

The first part examines relevant objectives for building design. The pure physical view is not sufficient and needs an extension. Objectives that are relevant in this field concern, first, economic efforts and ecological effects; second, qualitative aspects need consideration such as aesthetics, the fulfillment of functions, and the feasibility of construction. That the latter aspects are not expressible by numbers calls for further interactive procedures, in which the judgment and preference of the designer is critical in the building design's optimization process. Sisk et al. (2003) state the demand for such interactive procedures while presenting a dialog-based tool for skeleton design.

The decomposition of the design into a component-based optimization model, discussed in the second part, provides an important means for interactively handling the qualitative aspects. A flexible CAD-like approach with components comprising parameters, analyses, and constraints helps to manage the dynamic development in building design. Furthermore, the extension by group definitions and alternative systems implementations opens up latitude for optimization in the component system.

2 THE DEMONSTRATIONAL PROBLEM

The considerations on optimization for building design are introduced by a demonstrational problem that is a hall intended potentially for industrial use, for production of large objects, as a sports hall, or as an exhibition hall. The requirement consists of one large room with the specifications displayed in Table 1. The design idea is founded on a frame-based layout, such as shown in Figure 1. A directional layout is intended, which leads to two side and two front facades both equally treated. To support this idea, it is intended to emphasize the frame as an architectural element. Ideally, the designer thinks of a trussed structure. In this layout, a lot of possibilities for modification exist. For instance, changing the number of frames, the construction and material type of its members, the type of the façade, and so on might improve the design. In terms of optimization, these possibilities are design variables.

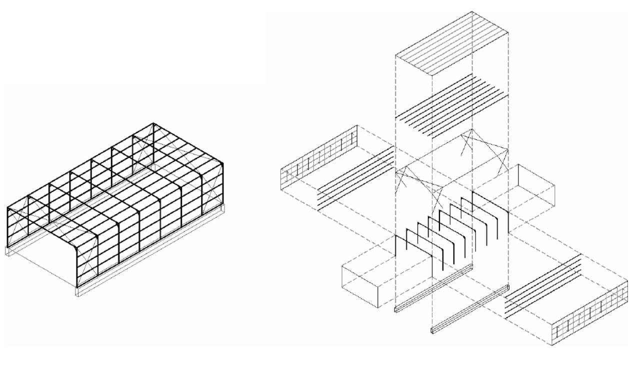


Figure 1. Demonstrational design for a hall.

Table 1. Specifications of the demonstrational design.

External parameters	Values / Description
Length / Width / Height	80 m / 40 m / 20 m
Total loads top / side	2.0 kN/m² / 1.0 kN/m²
Indoor Temperature / Heating Degree Days	18°C / 3300 °Cd
HVAC effectiveness / pipe diameter (passing through truss)	80% / 0.50 m
Opaque Façade (85%)	Metal sheet with expanded polystyrene insulation
Transparent Façade (15%)	Double glazing, metal frames
Lifetime	25 years

3 QUANTITATIVE OBJECTIVES AND CONSTRAINTS FOR BUILDING DESIGN

The formal method of optimization uses an objective function and constraints to describe the problem. The usual form is

minimize or maximize $J(x)$ (1)

with respect to $g(x) \leq 0$ and $h(x) = 0$ (2)

where J is the vector of the objectives and g and h are the vectors of the constraints for the problem. Using the methods of optimization is a matter of translating the design with its idea, its characteristics, its objectives, and its constraints to the given formalism.

First, I want to discuss the objective aspects. Typical approaches of structural optimization use stiffness and weight as objective criteria such as Koski (1988) or optimal material distribution while minimizing strain energy such as Bendsoe (1988). Such physical approaches might be appropriate for vehicles or airplanes since weight is an important aspect. For buildings, these aspects are of secondary interest. In contrast, for acoustical and thermal reasons, a high weight is sometimes desired. This illustrates that physical aspects such as the amount of material or the weight alone are not sufficient as objectives. Thus, an extension of the objectives is required.

3.1 *Resources*

An important aspect for the performance of a building is the required amount of resources. What is the economic expenditure for construction and maintenance during its life-cycle? How much materials of what kind, how much energy, and how much land is used? How much emissions will the building cause? These are questions that the persons involved in designing take interest in. Newer approaches established models considering these aspects while applying optimization to buildings. Grierson et. al. (2002) search for economic valuable design solutions of office buildings. Wang et. al. (2005) consider the life-cycle impacts by the consumption of environmental resources in an optimization model. However, these studies are general examinations but no real design optimizations since they do not deal with the situation of a specific design. In contrast, Lähr et al. (2005) present a study for an individual building design examining sensitivities of room climate and slab deflections to geometric parameters.

Although the physical properties of the design play a subordinate role, they provide the basis for determining the resources. Respective conditions of the environment serve to derive the resources from the physical properties. The quantity of a material or of a construction type causes costs, consumption of energy, or the emission of substances with environmental impact. Coefficients allow the deduction of the sums of economic efforts, resource consumption, and emissions. In my implementation, they are stored in the matrix **C** for each item, which depends on the ambient conditions for the design, such as the situation of the market and the current circumstances of production technology (Equation 3). Different situations for a building site need different coefficient matrices. However, if the place for a building is comparable, the matrix might be reused. This matrix is organized as a database of items used in the building design. A quantity vector q contains the reference for construction and for the life-cycle expenses. As units of the quantity, meter, square meter, cubic meter, kilogram, pieces and so on occur. The sum of the multiplication of the quantity q and the coefficients C summed up for the complete design yield the required resources r.

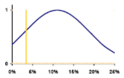
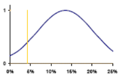
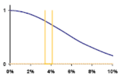
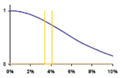
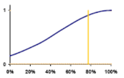
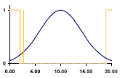
$$\mathbf{r} = \sum_{n=1}^{n_{item\ max}} \mathbf{C}_n \mathbf{q}_n \text{ with } \mathbf{C} = \begin{Bmatrix} c_{Costs,\,Construction} & c_{Costs,\,Life\text{-}Cycle} \\ c_{Energy\ non\text{-}renewable,\,Constr.} & \vdots \\ c_{Energy\ renewable,\,Constr.} & \\ c_{Global\ warming\ potential,\,Constr.} & \\ c_{Ozone\ depletion\ potential,\,Constr.} & \\ c_{Household\ waste,\,Constr.} & \\ c_{Special\ waste,\,Constr.} & \end{Bmatrix};\ \mathbf{q} = \begin{Bmatrix} q_{Constr} \\ q_{LC} T_{LC} \end{Bmatrix} \quad (3)$$

3.2 *Quantitative objectives that rely on preference*

In contrast to the resources, other objective aspects individually rely on the *preferences* of the designer; each of whom has his or her personal style, which calls for the integration of preferences in the objectives. Bailey et. al. (2006) presented an approach for optimizing the structural weight of trusses recording the preference of a user and considering it as an objective during an optimization with a genetic algorithm. However, besides the style of the designer, each design has its own context and its own expression. This causes difficulties in setting up a general objective function for such aspects as aesthetics or functional considerations and calls for an individual calibration of the preferences for each single design. For instance, one designer might like strong columns while the other likes slender ones. Similarly, in one design a girder with less height might suit better whereas in another one the girder needs a certain height to look good.

To consider these individual preferences, functional and aesthetic criteria for the geometry are implemented in the evaluation of the demonstrational system. They consist of ratios or geometrical measurement (Table 2). The interactive diagrams in Figure 2 illustrate the geometric criteria for the height of the frame member in relation to the hall dimensions and the frame distance with the ratios of the bays in the side elevation. Criteria such as the frame distance have functional as well as aesthetic effects since the possible width of a lateral entrance is determined and the appearance of the façade is affected.

Table 2. Preference criteria for function and aesthetics of the hall design.

Name	Function	Criterion	Description
P_1		Slenderness of horizontal member	Ratio of the member height to the overall height and width (see Figure 2)
P_2		Slenderness of vertical member	
P_3		Structure Transparency (hor.)	Ratio of the lateral view area of the structure to the overall view area of the building
P_4		Structure Transparency (vert.)	
P_5		Similarity horizontal / vertical truss	Similar ratio of height to width is rated high
P_6		Distance of the frames	Desired distance between two frames either for functional or for aesthetic reason

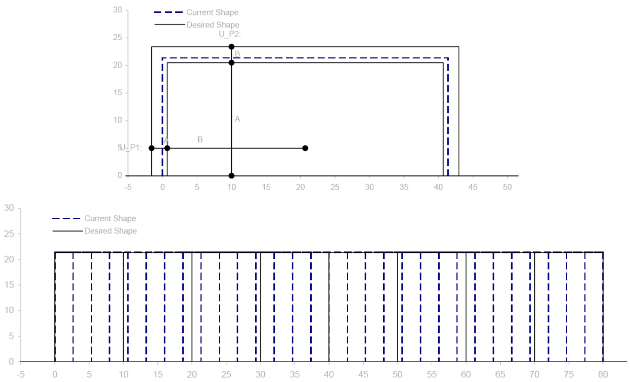


Figure 2. Aesthetic and functional criteria. (a) Ratio between truss height and hall dimensions (section view). (b) Number of bays between the frames or distance between the frames.

3.3 *Utility functions*

In order to asses dimensions, ratios, and values of the model, *utility functions* transform the physical values into a scale from zero (worst) to one (best). This approach is related to *physical programming,* which is developed by Messac (1996). As a core of the evaluation, the transformation by utility functions assigns a value to the numbers of the resources and preference criteria.

In the approach, two different utility functions were used. The first type, represented by the function U_Q, describes a situation in which a continuous increase or decrease of a function is a better result (Figure 3a). In the example, all resource criteria use this type of utility functions. The configuration for the resource criteria of the example is shown in Figure 5. Since for all these criteria a reduction is desirable, they follow a less-is-better assessment.

The second type marks a desired value as best and sets the decrease of the value for deviating by the sharpness S (Figure 3b). Thus, the sharpness determines how strict a criterion is applied. Furthermore, a utility below 0.10, respectively 10% performance, is considered as a constraint. A solution that has one utility below this threshold is excluded from the further optimization.

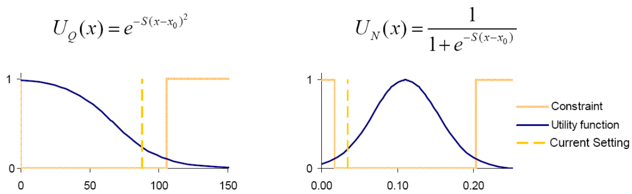


Figure 3. Utility functions for assessing values: (a) less-is-better and (b) nominal-is-better.

3.4 *Objectives in the example*

The objectives in the example are aggregated to three main groups (Figure 4). The first group comprises economic objectives, the second ecologic objectives, and the third consists of the preference objectives. All aspects are considered over the life-time period. Thus, J_1 comprises costs for construction, for maintenance including energy expenses as total costs for one square meter of the hall. The cost result from the specific cost data C_1 and the quantities q.

$$J_1 = U_{Q,1}\left(\sum_{j=1}^{3} \mathbf{C}_{1,j,n}\,\mathbf{q}_{j,n}(T_{LC})\right) \; with \; T_{LC} = 25 years \tag{4}$$

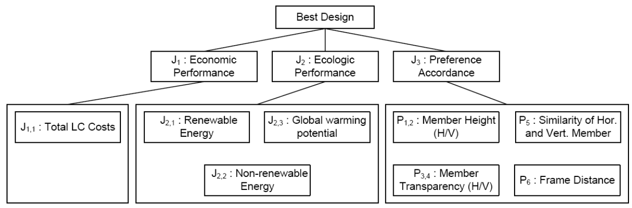


Figure 4. Structure of the objectives.

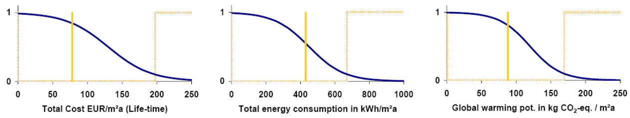


Figure 5. Utility functions for economic and ecologic performance.

The ecologic objective function considers the amount of not-renewable energy (based on $C_{2,j}$ in kWh/m²y), renewable energy ($C_{3,j}$ in kWh/m²y), and the emission of gases with global warming potential ($C_{4,j}$ in kg CO_2-equivalent/m²y). The data for this analysis origin from Eyerer (2000) and Kohler et al. (1995). The weighting w reflects the different environmental impact of not-renewable, renewable energy, and CO_2 emission. As the items is C and q include building materials and construction types as well as energy types for heating systems, costs, energy, CO_2 emission etc are considered not only during operation but also for production.

$$J_2 = \sum_{n_c=2}^{4} \mathbf{w}_{n_c-1} U_{Q,n_c}\left(\sum_{j=1}^{3} \mathbf{C}_{n_c,j,n}\,\mathbf{q}_{j,n}(T_{LC})\right) \; with \; T_{LC} = 25 yrs. \; and \; \mathbf{w} = \begin{pmatrix} 0.5 \\ 0.1 \\ 0.4 \end{pmatrix} \tag{5}$$

The third group comprises a set of six preference criteria for aesthetic and functional aspects. In contrast to the other both groups, they are adapted individually to the situation of the hall. These preference objectives, summarized in Table 2, provide a means to control the optimization process so that the design fulfills the desired function and matches the design idea.

$$J_3 = \frac{1}{6}\sum_{i=1}^{6} U_{N,i}(P_i(x)) \tag{6}$$

4 QUALITATIVE ASPECTS AND IMPLICIT CONSTRAINTS

The last sections only dealt with criteria that are expressible numerically. However, not all criteria are measurable and definable by numbers. Especially for aesthetic aspects, such as appearance, qualitative aspects of the design play an important role. Without taking them into account, an essential part of the objectives is not present. Carrying out an optimization only with a subset of relevant objectives does not lead to a sound result since the neglected objectives might perform poorly. Thus, a way of considering qualitative aspects is required.

The non-numerical character of the qualitative aspects excludes them from being evaluated adequately by a numerical optimization algorithm. However, the designer is able to judge the qualitative aspects with an interactive approach, in which he or she manages these aspects. As easy as it sounds, there are major differences between how a human designer and an optimization algorithm act. First, there is a large discrepancy in the number of possible evaluations. The algorithm is able to evaluate a huge number of designs in a relatively short time while the designer needs longer and gets tired with the increasing number of designs. Furthermore, the designer uses intuition to solve a problem. Thus, a far smaller number of designs is required as he or she has the ability to draw conclusions.

The Interactive Evolutionary Computation (IEC) examines the integration of human evaluation in an optimization procedure (see Takagi 2001 for an overview). However, the typical situations of IEC distinguish themselves by objectives that are only determined through human evaluation. In contrast, in building design, engineering aspects are of more or less equal importance to the aspects of appearance of the building. Therefore, a combination of the computational evaluation and the human assessment is required, which again gives rise to the problem of user fatigue.

For this reason, I propose to separate the loop of computational optimization from that of human design improvement (Figure 6). In a recurring inner loop, the computational optimization is carried out considering the quantitative objectives. In the outer loop, the designer defines the optimization model such that it includes the design idea. Having the results of an inner run, the designer changes the optimization model while considering the qualitative characteristics of the design. This means he or she trims the design back to the original idea or modifies this idea.

However, how do these ideas of the design come into the inner loop if they are not expressible by numbers? The key is the structure of the optimization model, i.e., the used components, the links between the components, and the allowed modifications determined by the design variables. No optimization model is completely neutral and allows all solutions. The model always comprises limits regarding the possible solutions and thus excludes other solutions from being reachable in the design space.

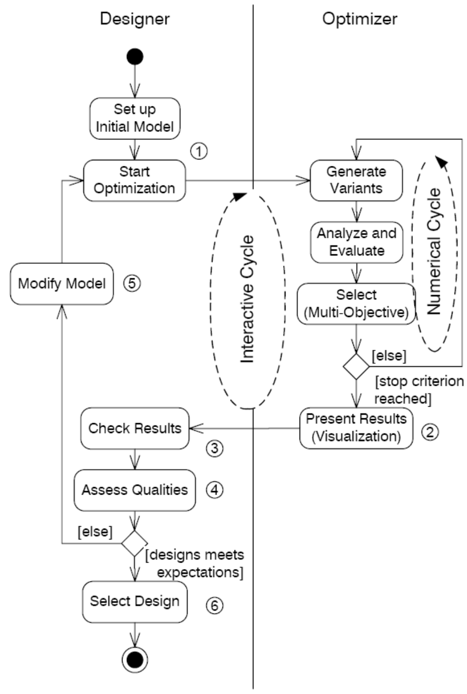


Figure 6. Workflow of optimization within the design process.

These limits by the structure of the model I call *implicit constraints* since they do on a non-numerical level what the constraints g and h (Equation 2) in the traditional optimization formalism achieve in the numerical realm. These limits provide the chance to implicitly implement qualitative aspects which the optimization should comply with. In the context of limiting the setting of design variables, Grierson et al. (2002) use the term *implicit constraint* in a more restricted sense. For reasons of production or standardization, only an enumeration of values is applicable for a design variable, a limitation they call implicit constraint. I understand all restrictions caused by the structure of the model as implicit constraints. Every setup of a model is able to favor and exclude certain designs in the solution space. The nonexistent neutrality of the design model is a chance to control the process while exceeding the pure numerical aspects.

For instance, setting up a system that consists of a frame-based design excludes other designs from being considered such as a grillage design. The system diagram (Figure 7) illustrates that the different design ideas lead to different structures of the system. In terms of traditional optimization, these are two distinct optimization models with their own independent design variables such as the number of beams or frames, the dimensions of the legs or columns and so on. However, from the viewpoint of the whole design process, both models belong to the same design space, which comprises all designs covering the desired space for the hall. So if the architectural design ideas consists in a directed frame structure, Figure 7a is a way to set up a model for conveying it.

The decision between these two alternative models or the generation of other alternatives by setting the structure of the model is an essential part of the design process. Thus, a quick method of setup is required to allow gathering results for each design variant and carrying out the trade-off between design idea and the numerical resources. For this reason, the next section deals with the setup of a flexible, component-based optimization model.

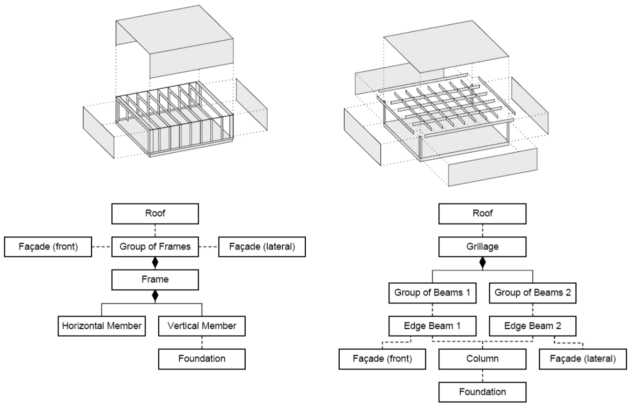


Figure 7. The structure of the model sets implicit constraints.

5 COMPONENTS

In order to capture the architectural intention as implicit constraints for the inner cycle, the decomposition with building-specific components is a key feature. Such components representing rooms, walls, columns, beams, section properties, joints, and so on serve to decompose a design idea into an optimization model. In this characteristic, they are related to the elements of modern building design software as they represent the building. However, for optimization, their functionality goes beyond that of only representation since they serve to set up a system by linking the in- and output parameters and comprise calculations for building a system.

The scheme of the components is based on two principles. First, a notion of function serves to determine and to differentiate the entities for setting up the model. Mitchell (1991) already worked with this idea of functionality in order to describe grammatically the structural design process of a primitive hut. In his approach, which I'd call a component grammar, a function of a beam is transferring distributed loads from its top to its supports. This notion of function I interpret in a broader sense and expand it to a multidisciplinary approach. For instance, a roof panel has a structural function; furthermore, it serves to define an architectural room, to separate indoor and outdoor space for achieving desired climate conditions, to provide light inlet, if skylights exist, and to comply with acoustic requirements. This illustrates that a component needs to fulfill multiple functions in different disciplines.

The second principle subsequently results from the first one. The function-based paradigm leads to a hierarchical approach (also called top-down approach) since an abstract component, defined by its functions, might need one or more subordinate components to fulfill these functions. A subordinate component might again consist of further components on the third level.

From the point of view of optimization, this hierarchical structure is of great interest, since it opens up the option of using different components for fulfilling a function defined on a higher level. For the subordinate realization of the higher level component, diverse components might exist. Thus, switching between these components might improve the design.

Two components have the same function if their structure of parameters coincides with that of the other component. In this case, they are replaceable mutually. For instance, for the frames in the demonstrational hall design, the replacement of profiled members with trussed members is possible since both are able to resist normal and shear forces as well as bending moments.

While setting up the component scheme, existing approaches for representing and exchanging building data have been taken into account. The most relevant definitions serving this purpose are the Industry Foundation Classes (IFC) and the ISO 10303 Standard. Furthermore, Rivard and Fenves (2000) present an interesting approach focusing on the representation of conceptual designs that extends the object representation by including requirements and evaluations.

5.1 *Bridging the gap between quantities and qualities*

One the one hand, one important task of the components is the representation. Based on the parameters they comprise methodical descriptions of how to generate a three-dimensional visualization or a drawing based on these parameters. A beam means extrude the profile along the direction vector given as parameter. The extrusion of the section shape yields to a number of faces. On the other hand, related to their generation method, the components furthermore comprise analyses or rather dimensioning. Given loads, support distance, section type, and so on, dimensioning of the beam leads to the required height, material amount, cost, and production energy.

Therefore, the components bridge the gap between the qualitative characteristics and the quantitative values. They link the architectural appearance and aesthetics to quantities of resources. They relate the qualities to the numerical world of optimization since a component has an appearance which affects the visual model of the design and, in the end, the component's dimensioning and analysis are part of the objective function and, thus, of the optimization model.

5.2 *The system of components*

The parameters of the components serve as interfaces to other components. They transfer and receive data of subordinate components. On the top level of the hall design, the model consists of the row of frames, the façades, the roof, the foundation, and the HVAC system (Figure 8). Descending the hierarchy, the row of frames, for instance, comprises the single frame, which again consists of the horizontal and the vertical members. The profiled mem

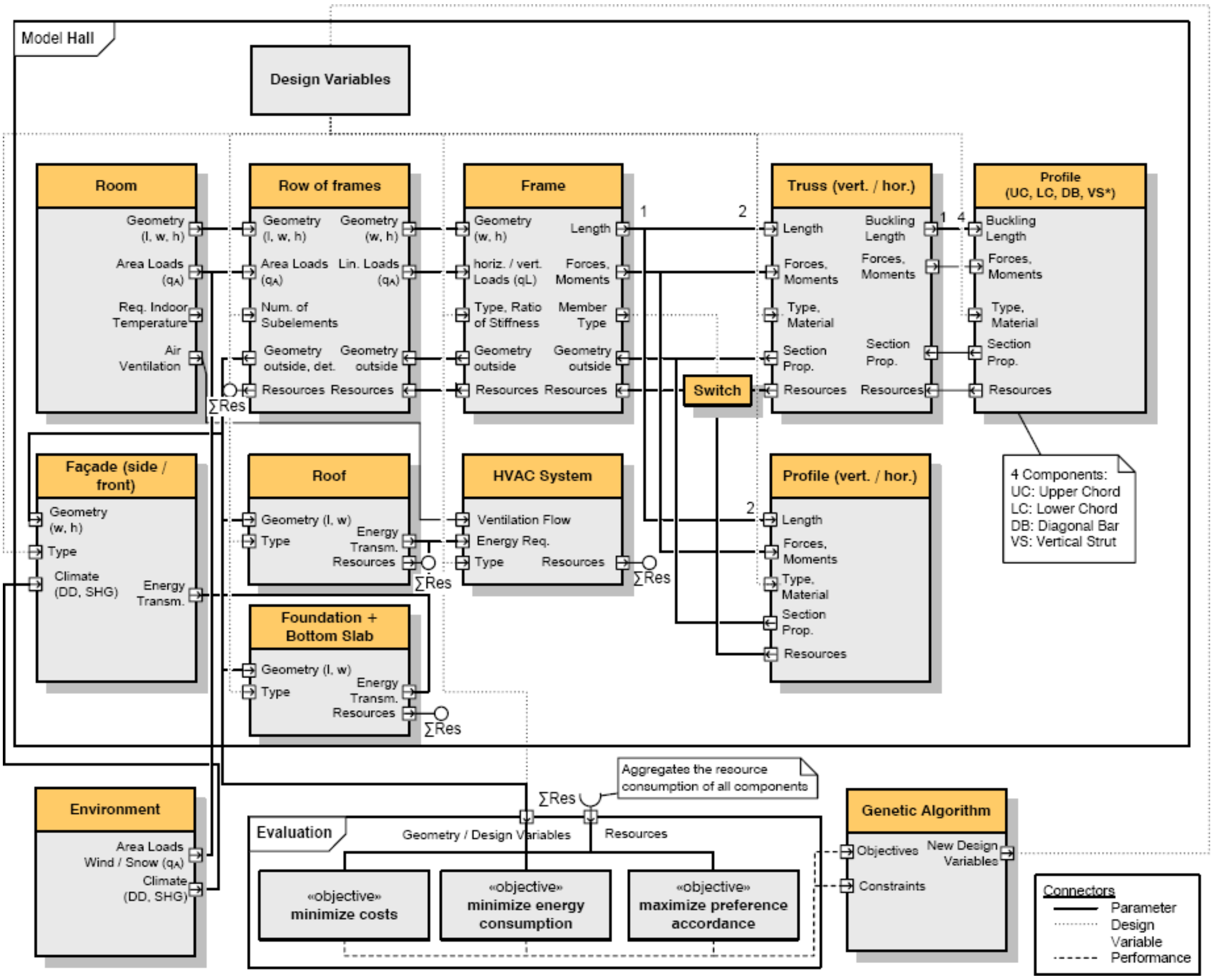


Figure 8. System of the hall optimization model.

bers are replaceable with a trussed member by means of the switches. A switch transfers, driven by a selection parameter, either the one or the other input and is used to implement system variations. The truss variant, however,uses new subordinate components, which are the lower and the upper chord, the diagonal bar, and the vertical strut. Additionally, it uses new design variables such as the truss height, the bay length and the truss type. For instance, the height of the truss can be chosen freely in a certain range and thus is a design variable. In contrast, the height for the profiled steel section is set by the dimensioning.

5.3 *Group components*

The grouping of entities is an important element of designing. It facilitates the production of the parts since repetition reduces the effort for planning and production and it is a means for supporting an aesthetic appearance. The recognition of an entity multiple times structures the design and introduces a regularity that is usually seen as pleasant. The internal logic of the group relation enables a viewer to understand a composition. Possible types of grouping are series, symmetries, or freely arranged repetitions of a part which furthermore might change its shape gradually.

Besides its function in designing, grouping opens up a possibility for optimization since the number of components within the group is changeable and thus a design variable. This affects the dimensioning of the elements in the group as discussed in Rivard et al. (2000). Furthermore, in the system, the dimensioning of the adjacent component is also affected since, for instance, its span of this component is changed.

6 OPTIMIZATION OF THE DEMONSTRATIONAL PROBLEM

For the hall example, several optimization test runs were carried out. The results of one run presented in this section are based on the assumptions for the design requirements and on the environmental conditions shown in Table 1. As the focus of the project deals with the development of an adequate model rather than new algorithms, the experimental implementation uses a commercial MDO software (ModelCenter, Phoenix Integration, Inc.). A genetic algorithm with a multiple-elitist strategy was chosen as optimization algorithm because of the mixed discrete-continuous characteristic of the task, although, of course, other algorithms would serve this purpose. The strategy of this algorithm yields a set of designs that are not dominated by other designs, i.e., Pareto optimal designs. During the test, it turned out that 50 to 100 individuals per generation led to an acceptable diversity for the number of design variables in the problem.

6.1 *Results of the test run*

Because of the three major objectives $J_{1..3}$ mentioned earlier, the solutions depending on their performance spread in a three-dimensional space. The filtering of the 150 Pareto results for features and feature combinations – such as similar member heights, material types, or member types – served to identify the four main groups of solutions (Figure 9). For this comparable small number of features and the low dimensionality, a manual control of the filtering is possible; but for a more complex problem or in the context of a routinely application, an automated filtering and group identification would be helpful.

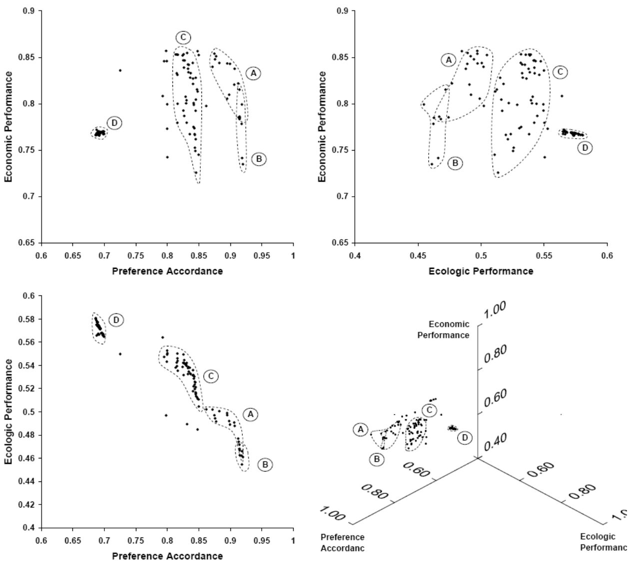


Figure 9. Pareto optimal results for the demonstrational hall.

The groups mainly exhibit common settings for the design structure and therefore, have a similar appearance. Figure 10 shows visualizations of selected representatives for each group. The designs of types A and B with trussed members at the top and the sides comply best with the preferences, which the both left diagrams in Figure 9 show. The preferences for the desired member height $P_{1,2}$ and for a high transparency of the frame members $P_{3,4}$ (Table 2) set the intention. Consequently, D is the poorest design as it uses thin profiles that do not significantly emphasize the frame structure. Furthermore, a low sharpness S of the preference function P_5 for the similarity of the horizontal and vertical member allowed designs with different member types, such as C. Raising the sharpness will exclude such designs. Moreover, B is a variation of A in the respect that it uses steel instead of wood. Therefore, its section measurement is less and it performs slightly better with respect to the preference accordance. In contrast, the performance of steel with respect to the cost and ecologic impact is worse.

Table 3. Design variables and objective values for Pareto optimal representatives.

Design Variable	Unit	Range / values	A	B	C	D
Number of frames		6..40	25	20	20	22
Base Bearing		Hinged, Fixed	Fixed	Hinged	Fixed	Hinged
Façade, Insulation (U-Value)	W/m²K	0.1...2.0	0.4	0.3	0.4	0.1
Horizontal member						
Number of truss bays		4..30	13	19	10	-
Material		Steel, Wood	Wood	Steel	Wood	Wood
Type		Truss, Profile	Truss	Truss	Truss	Profile
Height	m	0.50...4.00	2.27	2.20	2.12	(0.70)
Vertical member						
Number of truss bays		4..30	7	10	-	-
Material		Steel, Wood, Concrete	Wood	Steel	Wood	Wood
Type		Truss, Profile	Truss	Truss	Profile	Profile
Height	m	0.50...4.00	1.79	1.74	(0.65)	(0.70)

Objective	Range	A	B	C	D
Preference Accordance	0...100%	89%	91%	84%	69%
Ecologic Performance	0...100%	50%	47%	54%	57%
Economic Performance	0...100%	81%	81%	83%	77%

Values in parenthesis ( ) are no design variable but result from dimensioning.

In terms of ecologic impact, design type D performs best. The consideration of its strategy makes this understandable. D is the design with the best insulation and the simplest load-bearing structure. Thus, the strategy of this design consists in investing the savings of the structure in insulation. As a result, designs like D achieve energy savings and reduction of CO_2 emission of 10 to 15 % in comparison to the design type A. By not allowing HVAC pipes to be ducted through the truss, design D needs more height for its profiles located above the pipes. This increase of height causes more volume to be heated, façade to be built and more heat transmission through the façade. To compensate these effects, additional insulation is required. Thus, this design type has higher costs and, therefore, performs less well in terms of economics.

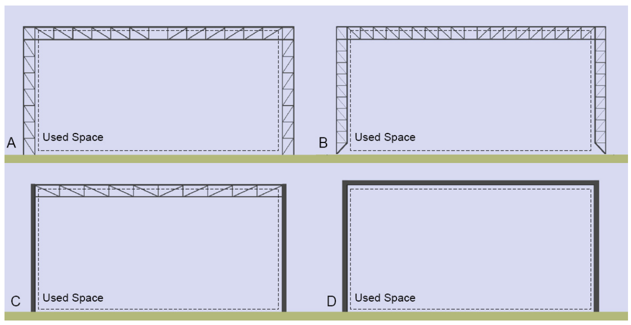


Figure 10. Visualizations of one frame for a typical design of each Pareto group.

Considering ecologic and economic performances, the design type C seems a good compromise. It achieves a good ecologic performance by reducing volume and surface of the building. At the same time, this reduces the costs of the façade and – as construction costs of the façade are about 25% of the total life-cycle costs – lowers overall costs significantly. Therefore, the ducting of the pipes through the truss that allows the decrease of the building's surface and volume – rather than the reduction of material by the truss construction – reduces the construction effort and resource consumption of C compared to the other designs. Apart from that, the reduction of the material cost by using the trussed construction is nearly compensated by the additional costs for the joints.

6.2 *Interactivity*

After setting up the optimization model and starting the optimization (Figure 6, No.1), the designer receives the results (No. 2) with visualizations in diagrams similar to Figure 9 or in three-dimensional representations similar to Figure 10. On this basis, the checking of the results (No. 3) and the assessments and management of qualities (No. 4) is possible. Subsequently, the designer either decides to change the component system or the objective weighting in order to include other variants or to adapt the system better to his preference (No. 5); or the selection of one or more designs finishes the design session (No. 6). The process of changing the model ideally equals the usual CAD-drawing process apart from using the specific components instead semantically undefined lines and circles.

The test run of the demonstrational design represents only one step in the design process. That step being completed, the designer might select one design and proceed with detailing, or he or she might change the model by disabling actual design variables, by enabling other parameters as design variables, or by adding a column-beam based design or a grillage as an alternative.

7 DISCUSSION

The optimization of the inner loop is incomplete in terms of objectives, and only the outer loop represents the complete evaluation. Therefore, it might be useful not only to include Pareto optimal designs in the inner results but also to include suboptimal configurations, because these configurations might perform well in the outer loop and, thus, compensate deficits of the inner loop.

A shortcoming of the current model is that it implements only the frame structure. In future work, further alternative systems such as a column-beam variant will be set up and implemented. Furthermore, the material concrete, not considered in the current model, will be added as an option in the next model.

Unfortunately, the present optimization software is not flexible enough to enable modifications of the model during the design process in a simply way. Currently, it is necessary to set up each system alternative, such as the replacement of the profiled member with the truss, manually in advance. A future environment should be able to perform component-operations in order to include system modifications in the optimization easily.

At present in CAD, the turn from a semantically poor, graphics-only based approach to a semantically enriched, domain specific design environment is occurring. Objects are set up to represent building parts and standards, such as the previously mentioned ISO 10303 and IFC, serve to exchange not only drawings but also describing elements and links between components. The extended components, proposed in this paper, represent a way of including description of variability as well as analysis and objectives in a building model. Thereby, the model evolves from a building description for one design only to an optimization model. Besides allowing the application of optimization algorithms, the formalization also supports communication since an engineer working on the design after the designer knows more about the latitude for modifications for improvement.

Moreover, as designing is a creative process, the catalogue of components is supposed to be an open structure, in which new components can extend the basic structure, if necessary. Basic components serve the daily tasks whereas user defined components provide an adaptation to special tasks.

8 CONCLUSIONS

The demonstrational problem illustrated how MDO can be applied as a tool in the design of buildings and how it can support design decisions by gathering information about the solution space. The characteristics of the objectives, especially the importance of qualities such as aesthetics, calls for an interactive procedure. In order to use optimization interactively embedded to the design process, a component scheme as outlined is an essential part of an environment in that the user can set up a model as easily as it is possible in current CAD systems. Besides representation, the components play a crucial role since they bridge the gap between numerical calculations of optimization and qualitative considerations of building design. Therefore, this approach provides a basis for using optimization as a supporting tool in the building design process. An ideal future scenario of design would include MDO as a performance driven search tool in CAD applications for building design which exceed pure drawing.

8.1 *Nomenclature*

x	Vector of design variables
J	Objective with a range from 0 to 1
J(x)	Objective vector as a function of the design vector
g(x), h(x)	Constraint function vectors
$U(x)$	Utility function
S	Sharpness of the utility criteria
x_0	Desired value for a design variable
C	Matrix of environmental coefficients
c	Single resource coefficient
q	Quantity vector (materials, part etc.)
T_{LC}	Time of the life-cycle
w	Weighting factors
P_n	Preference (ratio of a geometric property of the design)

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