17th International Conference on the Applications of Computer
Science and Mathematics in Architecture and Civil Engineering
K. Gürlebeck and C. Könke (eds.)
Weimar, Germany, 12–14 July 2006

MODELS FOR MULTIDISCIPLINARY DESIGN OPTIMIZATION: AN EXEMPLARY OFFICE BUILDING

P. Geyer*

* *Dept. of Structural Design, Institute of Architecture, Berlin University of Technology,*
Strasse des 17. Juni 152, Sekr. A16, Berlin, Germany
E-Mail: Philipp.Geyer@TU-Berlin.de

Keywords: Multidisciplinary Design Optimization, Component-based Optimization Model, Component-based Decomposition, Façade Optimization.

Abstract. *This paper deals with a method for applying Multidisciplinary Design Optimization (MDO) as a tool for the designing of buildings. An optimization model is established considering the fact that in building design the non-numerical aspects are of major importance than in other engineering disciplines. A component-based decomposition enables the designer to manage the non-numerical aspects in an interactive design optimization process. A façade example demonstrates a way how the different disciplines interact and how the components integrate the disciplines in one optimization model. In this grid-based façade example, the materials switch between a discrete number of materials and construction types. For light and thermal engineering, architecture, and economics, analysis functions calculate the performance; utility functions serve as an important means for the evaluation since not every increase or decrease of a physical value improves the design. For experimental purposes, a genetic algorithm applied to the exemplary model demonstrates the use of MDO in the design process.*

1 INTRODUCTION

The mathematical and technical foundations of optimization have been developed to a large extent. In the design of buildings, however, optimization is rarely applied because of insufficient adaptation of this method to the needs of building design: Structural optimization, for example, normally uses the amount of material and the stiffness of a structure as objectives for optimization. In contrast for building design, other aspects from a couple of disciplines are relevant, such as economics, structural, lighting, and thermal engineering, fire protection, acoustics as well as architecture, with its concern for aesthetic and spatial appearance. Some aspects of these disciplines are of non-numerical nature and therefore, require an interactive approach.

In aerospace technologies, the method of Multidisciplinary Design Optimization (MDO) has been developed which is capable of handling the specific challenge of optimization in the design process. For transferring this method to building design, the setting-up of a specific component-based optimization model is required.

For the demonstration of the application of MDO in building design, this paper deals with a façade in front of an office room as an example. This part of a façade as shown in Figure 1 might be added up to a whole façade of an office building. This exemplary model needs to consider the engineering aspects, i.e. primarily that enough natural light is provided for the room behind the façade and that the thermal energy loss is minimized. From an economic point of view, the costs of the fabrication should be kept within a limit. For architectural reasons, transparency is desired in certain areas of the façade: first, to have a connection to the outdoor space in order to improve indoor space quality, and second, to achieve a certain exterior appearance of the building. Since multiple disciplines are involved, a solution is necessary that performs well with respect to all disciplines. Setting up an optimization model will show the interaction of the different disciplines for the façade component.

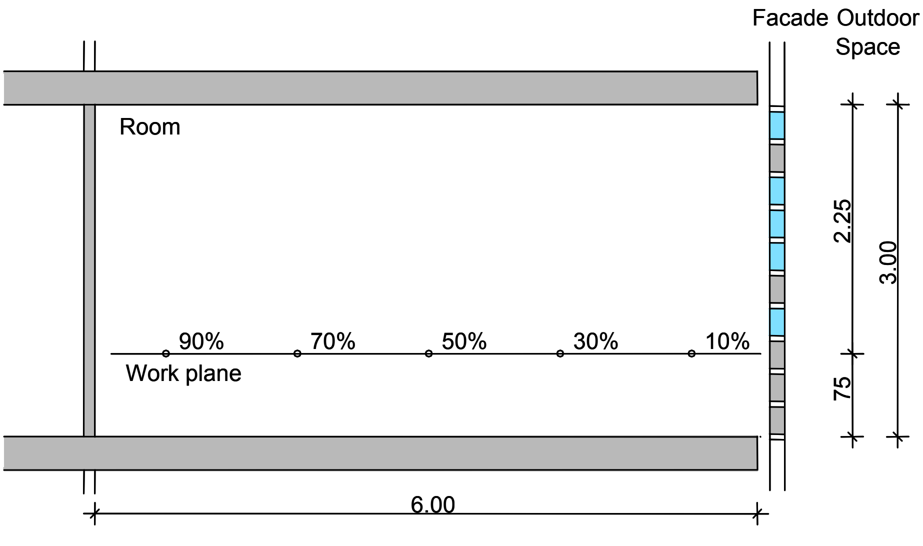

Figure 1: Office room with façade.

In general, the design of the façade has to guarantee the minimum degree of performance for each discipline in order to comply with regulations, for instance, providing enough daylight at the workplace. Second, the multidisciplinary optimization seeks to improve the performance of each discipline with respect to the whole model.

The paper attempts to show the implementation of the different disciplines in one optimization model and to consider optimization as a tool supporting the design process. The façade is used as a representative for other components of a building design in order to demonstrate how the disciplines intersect at a component and how a decomposition in terms of parameters, analyses, objectives, and optimization can be implemented.

2 MULTIDISCIPLINARY OPTIMIZATION FOR BUILDING DESIGN

2.1 Objectives, Constraints, and Design Variables

For applying optimization in building design, it is essential to consider all relevant aspects, which raises a multidisciplinary problem. Other objectives than the physical ones, applied for example in structural design, are important: objectives such as low costs, sustainability in constructing, functionality, aesthetic appearance and constructional feasibility. As discussed in a previous paper [2], I would like to group the objectives into three categories: the first covers pure physical objectives such as the amount of material; the second non-physical objectives, which are describable by numbers such as costs. The third group includes those objectives which cannot be expressed by numbers. Therefore, an optimization algorithm is not able to manage these aspects adequately. Consequently, I propose the integration into the optimization process as constraints which are changed interactively during the design process.

The first kind of constraints are the conventional ones established as equations and inequations. They are, for example, used for considering limitations of the material thickness with respect to fabrication. These constraints might also serve to achieve an appearance aesthetically desired. For instance, the height limit imposed on a beam can serve to attain a slender appearance of a construction. However, a means at least as powerful as these for determining the design space is the structure of the model itself. The structure decides which solutions are found and which are not accessible and so constrains the design space in an indirect way. Thus, I call them implicit constraints. These constraints might have a greater influence on the solution than the numerical constraints.

For building design, it is of major interest that the implicit constraints are able to include non-numeric information. Therefore, they can serve to consider aspects like aesthetic or function aspects in the design process. The façade example is based on a cellular structure to whose cells different materials are assigned. Figure 2 shows an example for such a grid-based Façade. This design idea of using a grid of cells and assigning different materials strongly constrains the design optimization. This is an aspect that cannot be expressed by numbers or result from any analysis. The designer needs to set up this idea in advance for serving as a framework. This idea consists in the arrangement and behavior of subordinate components, possibilities of changing the design, which are the design variables, and the underlying analyses. Therefore, the decomposition of the design into a system of components, which is discussed in the next section, is of major importance.

Figure 2: Grid-based design of a façade for Simons Hall
in Cambridge, Massachusetts (Architect: Steven Holl, [3]).

Since some of the aspects cannot be handled numerically and require an interactive human intervention, two different loops in the design process result: the inner loop consists in the *numerical optimization* executed by an algorithm, whereas the outer loop is the *design exploration*. This exterior loop is executed in dialog between human and machine and serves for setting up the model and the related constraints as well as for reflecting upon the results afterwards and reacting by changing the model.

3 DECOMPOSITION

In this interactive context, the process of decomposition, the description of the design as a system of components linked by parameters, provides an important means for setting implicit constraints and assigning non-numerical characteristics: For instance, the naming and handling a part as a beam, as a frame or as a truss define important characteristics with respect to its function and appearance. Numbers cannot express these characteristics. Therefore, decomposition sets non-numeric characteristics as implicit constraints. Among these characteristics are architectural appearance as well as producibility and concepts of production.

3.1 Component Decomposition

During decomposition of the design, the disciplines intersect at the components as shown in Figure 3. The façade component has to fulfill functions and demands defined by the disciplines. The properties and the configuration of the design variables serve to meet these demands. The disciplinary analyses provide the data to confirm the performance of the component. For the exemplary case, the façade in front of one room is subjected to optimization. In other cases, other components might be chosen for optimization and their parameters might be turned into design variables.

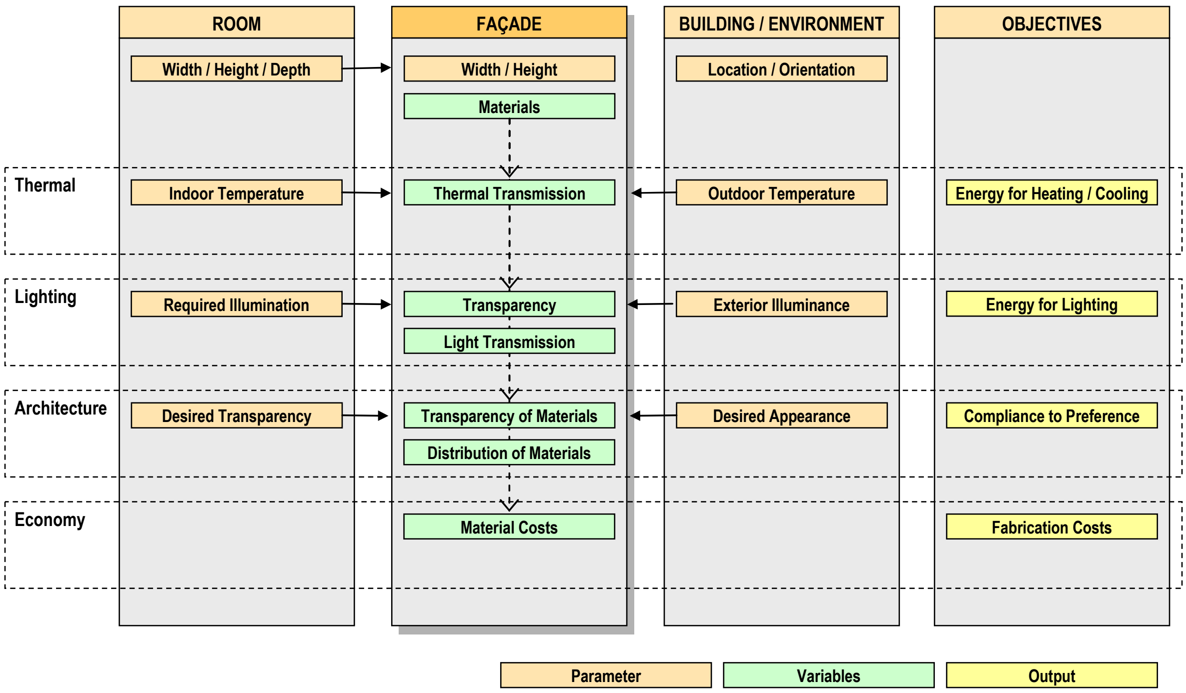

Figure 3: Decomposition showing the disciplinary intersections at the components.

All variables in the façade example depend on one matrix that describes the distribution of the materials. This matrix is the basic design variable. It is a 10 x 10 matrix with discrete numbers representing material and construction for each cell (Figure 4). Three different types of material are considered: which are glass, a semitransparent material, and an opaque cladding.

3	3	3	3	3	3	2	3	3	3
2	2	2	2	2	2	3	3	3	3
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
2	2	1	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1

$$\vec{x}_m = \begin{pmatrix} x_{m\,1,1} & x_{m\,2,1} & \cdots & x_{m\,i,1} \\ x_{m\,1,2} & x_{m\,2,2} & \cdots & x_{m\,i,2} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m\,1,j} & x_{m\,2,j} & \cdots & x_{m\,i,j} \end{pmatrix} \qquad (1)$$

$$\vec{x}_m \in \{1,2,3\}\,;\; i, j = 1..Size \qquad (2)$$

Figure 4: Material matrix.

Furthermore, parameters are required to define the model of the façade. The location and the orientation of the building need to be defined as well as the dimensions of the interior room behind the façade and thus the width and the height of the façade portion itself. These parameters are relevant for all analysis modules. Other parameters, which are mentioned in context with the modules, are significant only to one module.

3.2 Analysis Modules

The *thermal module* calculates the energy needed for heating in the winter and for cooling in the summer. It considers thermal transmission as well as solar heat gain caused by radiation. The basic analysis equations are:

$$Q_H = DD_H \sum_{i=1}^{3} U_i A_i \tag{3}$$

$$Q_H = DD_C \sum_{i=1}^{3} U_i A_i + SHG \sum_{i=1}^{3} SHGF_i \cdot A_i \tag{4}$$

$$Q_{tot} = Q_H + Q_C \tag{5}$$

U_i Coefficient for heat transmission per material in (W/m^2K)
A_i Area per material (m^2)
$DD_{H,C}$ Degree days for heating and cooling (°C · days)
SHG Solar heat gain in one summer (W/m^2 per year)
$SHGF$ Portion of light passing through the material
Q_{tot} Total energy consumption
$Q_{H,C}$ Energy required for heating and cooling (kWh/m^2 per year)

Some of the parameters in this module, such as the degree days and the solar heat gain, depend on the location and orientation. The transparent area and the transmission coefficients depend on the configuration of the design variables. The module tends to turn all cells into opaque material since this configuration has the lowest thermal transmission.

The *architecture analysis module* uses a preference matrix for evaluating a design configuration. This matrix contains the location desired for transparent cells with respect to view and exterior appearance. An evaluation function in the architecture module compares the design matrix to the preference matrix and returns a value that describes the compliance with the preference. This module exemplifies a way how a visual intent might be implemented.

1	0	0	0	0	0	0	0	0	1
1	1	1	0	0	0	0	0	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1
1	1	0	0	0	1	1	1	1	1
1	0	0	0	0	0	0	1	1	1
0	0	0	0	0	0	0	0	1	1
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	1

$$P = \begin{pmatrix} T_{1,1} & T_{2,1} & \cdots & T_{i,1} \\ T_{1,2} & T_{2,2} & \cdots & T_{i,2} \\ \cdots & \cdots & \cdots & \cdots \\ T_{1,j} & T_{2,j} & \cdots & T_{i,j} \end{pmatrix}$$

P: Preference matrix for the transparent cells
T: Desired transparency

Figure 5: Preference Matrix for Architecture.

The *lighting module* calculates the light incidence based on the IESNA method (described in [7]). The module calculates the available illuminance at 70% of the room depth. This value should at least comply with the requirement of 300 lux. Furthermore, an increased value is beneficial. Therefore, this module is the driving force for glass in the façade.

Equation (6) shows the basic equation for this module and is executed for every cell. The approximations in equation (7) and (8) are used in order to automate the table-based IESNA method.

$$E_i = \sum_{c=1}^{100} \tau \left(E_{xvk} CU_k + E_{xvg} CU_g \right) \tag{6}$$

$$CU_k = (0.362\ RW^3 + -5.98\ RW^2 + 33.1\ RW + 0.0253) \cdot 0.0107 * RR^{-1.49} \tag{7}$$

$$CU_g = (0.26\ RW^3 + -4.1\ RW^2 + 21\ RW + 1.55) \cdot 0.0093\ w\_RR^{-1.28} \tag{8}$$

E_i Interior illumination (lux)
$E_{xvk,g}$ Exterior illumination sky and ground (lux)
$CU_{g,k}$ Coefficient of utilization
τ Transmission coefficient
RW Ratio window width to window height
RR Ratio room depth to window height

The *economy module* represents the costs required for fabrication. Depending on the material assigned, each cell causes costs that are summed up to estimated overall fabrication costs (see equation 9). This module reflects different costs for materials, production, and installation.

$$C = \sum_{i=1}^{3} c_{A,i} \cdot A_i + \sum_{i=1}^{3} c_{n,i} \cdot n_i \quad (9)$$

C	Overall costs of fabrication	n_i	Pieces per material
$c_{A,i}$	Costs per Area	A_i	Area per material
$c_{n,i}$	Costs per piece		

3.3 Utility Function and Performance

A simple “the more the better” or “the less the better” is inadequate for some objectives. For instance in case of lighting, an illuminance between 300 and 450 lux for the complete room is desirable, but to increase the illuminance for the 70% point does not necessarily improve the usability. In contrast, it might cause problems of glare in areas close to the windows. For this reason, a weighted sum approach, for example, seems to be insufficient, and the aggregated utility functions approach is necessary.

The utility function transforms the physical values such as the illuminance or thermal energy into a number between zero and one that expresses the value of the objective for the design. Figure 6 shows the exponential utility function used in the example. The lower threshold defines the point from which a design is acceptable and the upper threshold set the limit from which an increase of the physical value does not improve the design. The lower threshold provides a constraint for the optimization in order to exclude the unacceptable designs as infeasible.

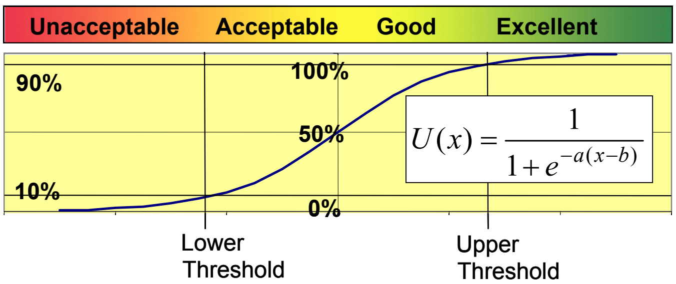

Figure 6: Utility function for assessing results of the analysis modules.

Objective	Range	Lower Threshold	Upper Threshold	Unit
Thermal (Total Energy)	0..70	30	15	kWh/m2y
Architecture (Transparency Preference)	0..1	50%	85%	-
Lighting (Illuminance)	0..2000	300	450	lux
Economy (Fabrication Costs)	0..1500	1000	300	$/m2

Table 1: Thresholds for the objectives.

In the aggregation, weighting factors w_i are implemented that assign importance to each objective (equation 10). Since the utility values are already normalized, scaling or unit problems are avoided.

$$J = \sum_{i=1}^{4} w_i \cdot U_i \qquad (10)$$

4 OPTIMIZATION TRIALS

For experimental purposes, an optimization algorithm was run using the described model. Due to the discrete variables in the material matrix, a genetic algorithm was chosen. Figure 7 shows the history of an experiment containing 25 generations with 30 individuals in the population. The result in Figure 8 shows the façade starting to open in the middle in order to comply with the used architectural preference matrix. The model is implemented using ModelCenter (PhoenixIntegration) and Excel (Microsoft).

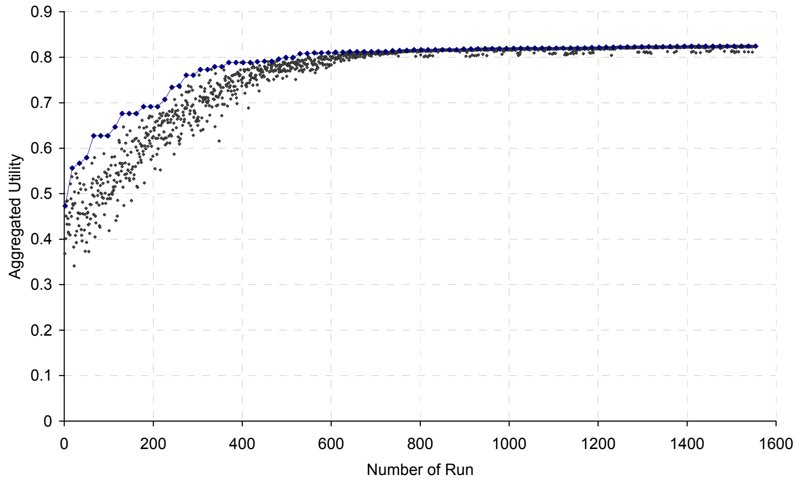

Figure 7: History of the experiment.

2	2	2	2	1	2	1	2	1	2
2	2	3	3	3	3	2	2	2	2
2	3	3	2	2	2	2	3	2	2
2	3	3	3	3	2	3	2	2	2
2	2	1	3	1	2	2	2	2	2
2	2	1	3	3	1	2	3	2	1
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	2
1	1	2	1	2	1	1	2	1	1
1	1	2	1	1	1	2	1	1	1

Figure 8: Resulting configuration of the optimization experiment
(1 = opaque, 2 = semitransparent, 3 = glass).

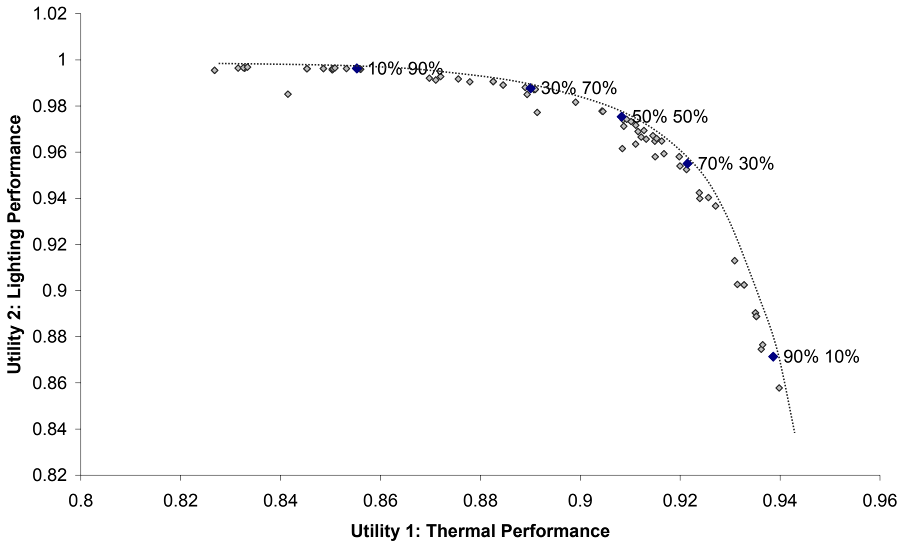

Figure 9: Multidisciplinary trade-off study between lighting and thermal performance.

5 CONCLUSIONS

A multidisciplinary approach is required for applying design optimization to building design. A proceeding considering only one discipline is not satisfactory since it leads only to a good solution for a part of the problem but not for the whole design. Only to consider all relevant disciplines in one model, as shown in the façade example, leads to an adequate result.

For the numerical objectives, the application of utility functions is necessary since not in every case an increase or a decrease of an analysis result improves the design. This allows assigning a threshold above that an increase does not lead to an improvement of the design or a threshold below that a performance is not acceptable.

For the non-numerical objectives, the decomposition of the system and the choice of components are very important. By this step, the designer includes non-numerical characteristics into the model, which provide implicit constraints for the optimization. In the example, the façade component was manually established with spreadsheet calculation; for the every-day use of design optimization it is required to have an environment with predefined standard components, which is extendable for special cases. The structure of such an environment is part of the future work. Furthermore, a good visualization is necessary in order to asses the appearance.

Besides the implementation of non-numerical aspects, the component-based approach has several advantages. First, it complies with the usual fabrication methods in building design. Second, CAD systems work object-oriented and this approach allows assigning analysis methods to the components. Therefore, a component-based approach provides a basis for an interactive and multidisciplinary design optimization.

Acknowledgements

The example of the façade originates from a project at the Massachusetts Institute of Technology (MIT) on MDO for Building Façades carried out by Anas Alfaris, Philipp Geyer, and Ricardo Merello, advised by Prof. Oliver de Weck. The collaboration was made possible by the invitation of Prof. George Stiny to the Design Computation Group at the MIT and by a grant of the German Academic Exchange Service (DAAD).

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