A GENERALIZED PRODUCT-MODEL BASED FRAMEWORK FOR MULTIDISCIPLINARY SENSITIVITY ANALYSIS AND OPTIMIZATION IN CIVIL ENGINEERING

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ABSTRACT

In this contribution we propose a generalized framework for multidisciplinary sensitivity analysis in civil engineering. We present a collaborative simulation environment for the optimization of human comfort in combination with static and geometric properties of a building section. The product model is based on the *Industry Foundation Classe*s (IFC) and extended for the needs of the simulation environment. Flow, temperature and humidity fields required for human comfort prediction are computed by a CFD kernel based on the Lattice Boltzmann method whereas the structure problem is solved by a high order finite element method. Multidisciplinary sensitivity analysis is applied to several examples and shows the potential impact of our approach.

KEY WORDS

Multidisciplinary Optimization, computing, Product model, Agent System, CFD, CSM.

INTRODUCTION

Collaborative planning in the design phase of buildings is often hampered by incompatibilities of the different mathematical or technological models (structural, topological, architectural, building services, "heating, ventilation and air-conditioning" (HVAC) and many more) and version inconsistencies showing up in case of parallel single model processing. It comes as no surprise, that multidisciplinary optimization of the functional design of buildings or building sections is very difficult as it depends on the reliable prediction of the impact of modifications of one model attribute for all other models.

For mass production applications multidisciplinary optimization (MDO) has been well developed and applied to large systems (see e.g. Sobieszczanski-Sobieski and Riley.1987, Kroo 1997). In contrast the product (construction) to optimize in civil engineering is usually unique which may be one of the main reasons why MDO here is still in its infancy.

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We propose a collaborative simulation environment approach, where an instance of an integrated product model is optimized by several coworkers. As an example case we consider the multidisciplinary optimization of human comfort in combination with static and geometric properties of a building section. These objective functions are naturally influenced by the HVAC installation (device locations, flow geometry, interior decoration etc.) as well as properties related to construction issues (wall openings for HVAC devices or doors might require modifications in the statics of the building section etc.).

PRODUCT MODEL

As a basis we use the *Industry Foundation Classe*s (IFC) (IFC 2006), a product model developed by the *International Alliance for Interoperability* (IAI), which is well suited for the needs of civil engineering. The design of the model is object oriented and the architecture of the model is organized in four different layers, from the *Resource Layer, Core Layer, Interoperability Layer* to the *Domain Layer*. To guarantee the modularity in the different layers, the design is based on the „*Gravity-Principle*“, meaning that each class of a layer can reference a class of the same or a lower layer. The IFC have not been developed to define classes for each possible object, but to describe and generalize the physical and non-physical objects in a construction up to a certain level. For a more specialized description of the objects the IFC proposes the *Property Set mechanism.* Here one can extend IFC classes with predefined or *Property Sets* of ones own to define attributes needed e.g. either by the Computational Fluid Dynamics (CFD) or the Computational Structure Mechanics (CSM) simulation. This includes the definition of entities like HVAC-Inlets and –outlets with appropriate attributes like boundary conditions and operational attributes like the characteristic curve, doors, windows with material parameters and boundary conditions (e.g. no-slip for CFD) but also sensor elements with *Property Sets* to collect and provide simulation results.

MODELER AND SIMULATION ENVIRONMENT

As we rely completely on the IFC standard we can use any modeler which supports this standard to define and alter a scenario. In order to provide a comfortable interface, a library with predefined objects, a powerful selection mechanism and automatic detection of the objects, we implemented and integrated these objects into the *Autodesk Architectural Desktop* (ADT) (ADT 2006), an extension of the common AutoCAD tailored for applications in construction of buildings. We used the *Object Modeling Framework* (OMF) (OMF 2006), the programming framework of the ADT, to implement the extended IFC objects. The design of the OMF is similar to the IFC product model. It supports a general and extendable building model where object attributes and geometrical information are separated and model elements can be linked to each other. A consistent conversion between both model types is supported. During import, the elements of the IFC product model are directly converted to AEC-objects of the OMF by utilizing a software tool (IFC-Utility 2x for ADT) which is a plug-in of the ADT. The IFCPropertySets, containing the data of the branches, are converted to AEC property sets during the process and can be accessed directly by the ADT. These data sets will be automatically extended by attributes for the CFD and CSM computation (like boundary conditions for temperature or material properties) during import.

SENSITIVITY ANALYSIS

Today, sensitivity analysis (SA) is applied in several disciplines, e.g. social, economic and financial science. In general sensitivity analysis is useful when using a surrogate model for a real system or process. Saltelli et.al. (2000) state that SA is a prerequisite for modeling. Due to SA's various application fields it is not trivial to give a complete definition for SA. Typically, SA addresses the question how a system's output behaves by varying its input.

System input is represented by input parameters and system output by response parameters, accordingly. Actually, additional parameters like fixed and noise parameters influence the system. Fixed parameters are constant during an analysis and noise parameters can vary within a certain range. The latter are representing uncontrollable system influence, for example wind or material properties. A specific configuration of input parameters is called system configuration or design. The set of input parameter combinations over their complete ranges defines a design space.

The goals of a SA are to identify essential input parameters that significantly affect the system response (response parameters), to eliminate certain input parameters by identifying parameters that cause hardly any system response alteration, to identify design space regions (system configurations) where the system behaves critical w.r.t. certain input parameters.

In the context of this contribution analytical solutions are not available at any point of the design space. For this reason many of the relations between the examined parameters can not be expressed analytically. In most cases it is not even known if they influence each other at all. Analysis of these relations is thus one of the main goals of the SA application in this context. Typically, all known information is based on discrete configurations (designs) of the design space. Hence, SA is applied for a surrogate model, which was created by discretized system information (see Jurecka (2004) and Lähr and Bletzinger (2005 and 2006)). Obviously, the amount (number of known designs) of information directly controls the accuracy of the model.

ANALYSIS RESULTS

The transfer of the computational results to the sensitivity analysis is achieved by attaching property sets to special sensor elements which were defined for this cooperation scenario. Theses sensors are simple *IFCProxy* elements with a cubic geometry. These elements mark the relevant measuring points in space. Data for different fields are extracted at these model coordinates and attached as property sets of the sensor elements.

In the following a brief overview of the analysis procedure is given. For more information on the relevant terminology we refer to Lähr and Bletzinger (2006). For an assessment of the available data, the analyst defines a (subjective) quality loss function Q which is composed of several response parameters with respect to the input parameters $\overline{\mathbf{x}}_i$. A general property of the quality loss function's definition is that low function values indicate preferable systems designs and vice versa. To construct Q it is necessary to bring together diverse types of response parameters by normalizing and scaling (assessing) them. Thus, preference functions p_k are applied to prefer or penalize values of response parameters y_k (where k = 1..n, where n is the amount of response parameters). Afterwards, an additional weighting parameter g can be applied for fading specific response parameter influences during the analysis.

$$\mathrm{Q_i}\,(\overline{\mathbf{X}}_i) = \sum_{k=1}^{n} g_k\, p_k\,(y_{ik}\,(\overline{\mathbf{X}}_i))$$

So far we have only discrete information at the computed designs $\mathrm{Q_i}$. A methodology named Kriging developed by Sacks J. et al. (1989) is used to create a surrogate model $\hat{\mathrm{y}}$ of the initial problem. This method also approximates system responses for designs, which were not computed before. This enables the analyst to estimate system behavior in the form of a quality loss definition Q, where Q is the response of the surrogate model $\hat{\mathrm{y}}$ for the totality of designs.

APPLIED METHODS

STRUCTURAL SIMULATION USING HIGH ORDER VOLUME ELEMENTS

The general procedure in structural analysis is to decompose any building model into different types of structural systems, like beams, plates or shells and to analyze each of these structures almost independently. This procedure has some drawbacks. One is that the individual analysis of each sub-structure might lead to mechanical inconsistencies; the other is that different kind of numerical systems are involved. Difficulties arise, when these systems must be coupled, when modifications require the change of the underlying mechanical model or when different levels of detail are considered. This may lead to inconsistency problems – geometrically as well as mechanically – which is a drawback especially in a multidisciplinary environment, when most of the tasks should be performed automatically.

We follow a different approach in structural analysis. The main ideas are to model structures entirely with continuum elements and to always compute structures as a whole, even when only details are considered. As an alternative to the commonly used dimensionally reduced formulations, we apply a strictly three-dimensional continuum approach of high order (Szabó 2003). Since the so-called *p*-version elements allow very large aspect ratios (up to a few hundred), apart from solid structures also thin-walled and beam like structures can be modeled efficiently in 3D (Duester 2001). In order to organize the solution process the finite element analysis is embedded into a framework which is based on hierarchy and sub-structuring concepts. Applying hierarchic sub-structuring, the finite element model can be modified locally while the solution is always computed for the global system (Niggl (2006), Mundani (2006)).

We integrate the finite element analysis into the multidisciplinary design process by deriving a finite element mesh of hexahedral elements from an IFC building model (Romberg 2004). However, the IFC model itself is not directly adequate for a numerical simulation, as it only implicitly describes the topology and the mutual connections of different structural components. The IFC-standard, for example, allows to define a room by its floor plan and corresponding heights, and openings for windows in a wall by their relative position to an 'anchor point'. To make the topology and the connections explicit, we derive a boundary representation model (BRep-model) with attributed objects (van Treeck 2004). This explicit BRep model is the basis for deriving the hexahedral finite element mesh. This process is based on a mainly macro-based approach. The model is decomposed into simpler geometric objects, where each object is meshed almost individually using the algorithm which fits best. For example, shell like structures are meshed by applying a 2D mesh generator and by extrusion to the 3rd direction, beam like structures are meshed by a purely macro-based algorithm. Before the objects are meshed, so-called connection elements were created on the intersection between two neighboring objects. These connection elements are then responsible for ensuring mesh consistency between each object.

FLUID DYNAMICS SIMULATION WITH LATTICE BOLTZMANN METHODS

The *predicted mean vote index* (PMV) is an empirical equation for predicting the mean vote on an ordinal category rating scale of thermal comfort of a population of people. The ISO (International Standards Organization) Standard 7730 (ISO 1984), "Moderate Thermal Environments -- Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort," uses limits on PMV as an explicit characterization of the comfort zone. For the computation of the PMV we need different input parameters like velocity, temperature and humidity of the air, turbulence intensity, radiation temperature and the clothing index and metabolic rate of the persons in the room under consideration.

The CFD kernel ‘Virtual Fluids’, which is based on the Lattice Boltzmann (LB) method (Qian et al. 1992, Krafczyk et al. 2002, van Treeck et al. 2005, Geller et al. 2005), is used to compute the velocity, temperature and humidity distribution of the air. The simulation of the fields is a transient, three-dimensional simulation, where a *Large Eddy model* (LES) is used to account for turbulent effects. The LB method is usually based on Cartesian grids and has been proven to be an efficient and competitive flow solver (Geller et al. 2005). The code works parallel with asynchronous communication on a 120 CPU cluster.

As in the CSM case described above, we use the derived BRep-model with attributed objects to process the geometrical information. The octree based grid generator maps the BRep-model to the Cartesian grid accounting for physical object attributes and boundary conditions.

EXAMPLES

As an example case we consider the optimization of human comfort in combination with the static and geometric properties of an office building. Figure 1 (a) shows an isometric view of the office building, Figure 1 (b) shows a top view of the open-plane office. The first two examples represent an intradisciplinary CFD/CSM analysis and optimization, the last example considers the multidisciplinary analysis and optimization.

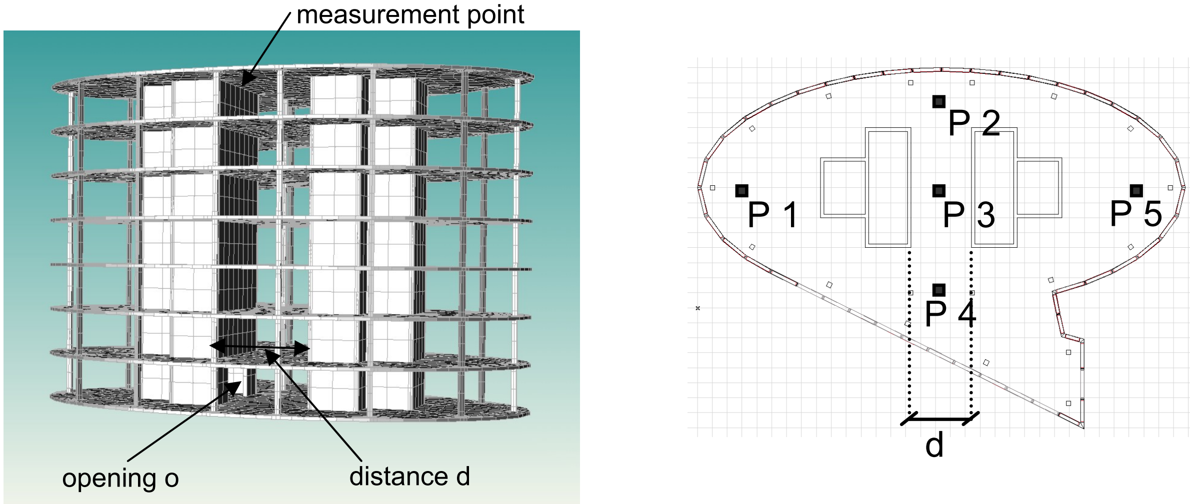

Figure 1: (a) isometric view of office building (b) top view of open-plane office

INTRADISCIPLINARY CSM-ANALYSIS

In this example we analyze the horizontal and vertical displacements of our structural model under the influence of several parameters. Our goal was to identify important system designs and thus the corresponding parameters which control the monitored displacements in these regions. At first, we defined 6 input parameters: x, y and z as the coordinates of the displacement measuring points as well as the following design parameters: o for an opening at the core base, d as the core distance, and V as the wind direction (see Figure 1 (a)). Output parameters were the horizontal and vertical displacement u_h and u_v, respectively.

Usually, the problem is to manage the huge amount of data produced during the computations and bring it to a suitable form for the analysis. In this case we have a seven-dimensional design space with six input and one response parameter. As in the example before the response parameters are assessed by preference functions. An optimal value for a displacement makes no sense, so we define a limit of $u_{h,max} = u_{v,max} = 2.5$ cm. Afterwards, we are able to search our design space for this border. Depicted in Figure 1 (a) is an identified reference point for a critical displacement u_h.>= $u_{h,max}$.

This identification enables us to eliminate x,y and z from the design space such that only 4 dimensions remain. Now we can display that point of the design space and it's surrounding with respect to the remaining input parameters o, d and V. Thus, we may deduce the contributions of the input parameters to the critical displacement u_h.

From the quality function given in Figure 2 (a) we can deduce that o becomes significant at high d, while at low d it is completely irrelevant with respect to u_h. Another factor is the wind direction, whose influence is obvious in Figure 2 (b). Here, also the correlation between wind direction V and the core opening o can be observed.

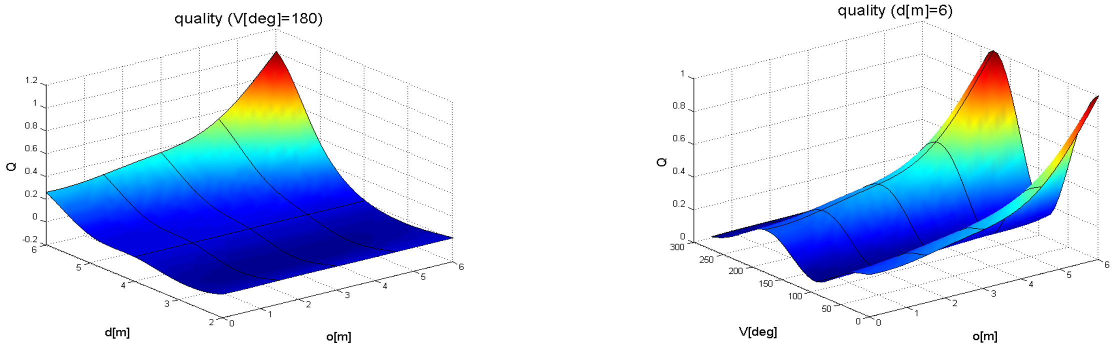

Figure 2: (a) quality over d and o, (b) quality over V and o

INTRADISCIPLINARY CFD-ANALYSIS

In this example the cost-value ratio of several versions of a HVAC installation are analyzed. Figure 3 shows the top view of the open-plan office with four expansion stage instances of the HVAC system, each representing different installation and material costs. The first version features air conditioning inlets next to the glazed facade at the west and east side with a cost factor of 1.2. Version two has inlets in the north and south side with a cost factor of 1.0 and version three has a full air-conditioned glazed facade with inlets all around and a cost factor of 1.8. The fourth version with a factor 2.5 of the costs extends the third version by swirl inlets aligned as a grid all over the floor.

Classically, the model is manually adapted by the control engineer and HVAC installations are implemented including elements of measuring-, operation- and control-engineering. In our approach these elements are emulated by a software agent framework which integrates the necessary controllers for the HVAC installation as software modules.

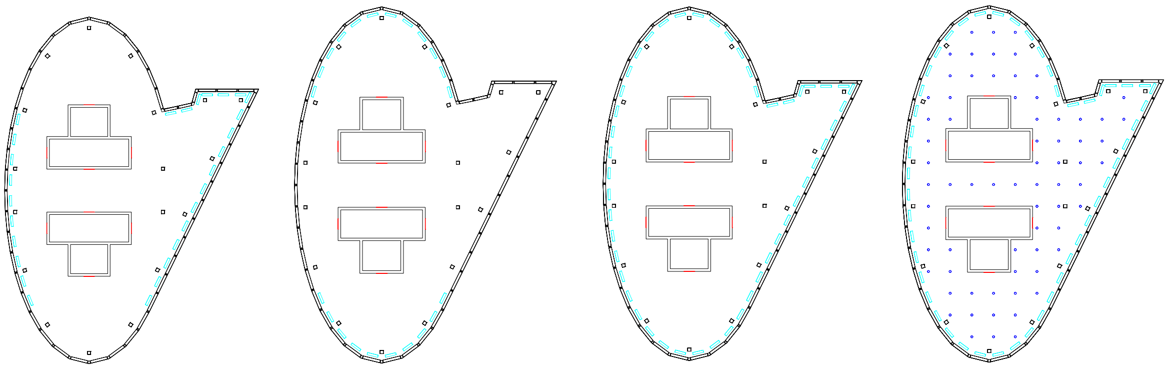

Figure 3: Different expansion stages of the HVAC system; Left to right: Version 1 to 4.

As a scenario we consider the heating of the initially cold office. The performance of the HVAC installations is analyzed by evaluating the PMV index of five measuring points at specific coordinates within the room shown in Figure 1 (a) for a steady state. Also the time variable trend of the room climate is considered in the analysis by integrating the PMV index over the cooling time period at the five locations.

We analyze this setup with the response parameters *PMV*, *cost* and *PMV over time* with corresponding weightings g_1, g_2 and g_3. Assessment of the quality loss of the response parameters is applied as displayed in Table 1.

response parameter	optimal value	inacceptable value
PMV	min	PMV > 2
cost	min	cost > 2.5
PMV over time	max	min(PMV_t)

Table 1: Assessment of response parameters

As described in section *Analysis Results* the application of preference functions transforms the response into the quality loss function *Q*. Furthermore, we investigate the influence of the input parameters *position* (measuring points), *version* (see Figure 3) and geometric information *x*, *y* of *position*. Favorable designs or system configurations yield low values of the quality function.

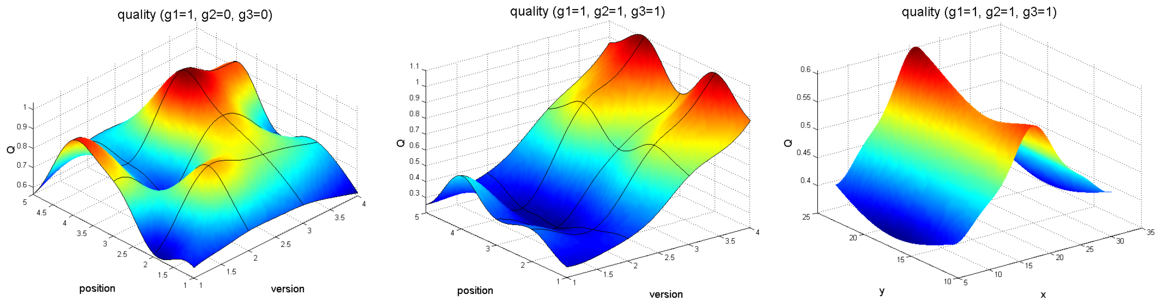

Figure 4: (a,b) quality over position and version, (c) quality over space

In Figure 4 (a) only the response of *PMV* is evaluated (g_1=1, g_2=0, g_3=0) and displayed over the input of *position* and *version*. Here the surprising result is that the most expensive expansion stage (version 4) is not superior to the other variants but on average is comparable to version 2. This is due to high velocities at position 4 (see Figure 1 (a)) degrading the PMV index. Fading in *cost* and *PMV over time* (g_1=1, g_2=1, g_3=1) leads to a quality loss function depicted in Figure 4 (b). With this information we can identify a decent system behavior for *version* 2. This is mainly due to its favorable costs. Finally, for the chosen *version* 2 we evaluate the quality loss over *x* and *y* (Figure 4 (c)). The negative influence of *PMV over time* for this configuration is obvious in the quality function and results from the chosen *version*2. This becomes obvious if we take into account how this specific expansion stage looks like (see Figure 3), meaning that the *PMV averaged over time* is worst between the two cores of the construction. Clearly, this result depends on individual weighting and assessment (preference functions) for this application.

MULTIDISCIPLINARY ANALYSIS OF A BUILDING

In a multidisciplinary setup we compute the optimal distance d of the two cores of the construction with respect to the maximal displacement of the ceiling plate and the comfort (PMV index) at the five different locations.

The quality loss function again consists of assessed response parameters. Here, we considered PMV with the same assessment as in the CFD example and a maximum displacement of the ceiling plate of 2.5 cm. Thus, the analysis combines both disciplines and becomes interdisciplinary.

Depicted in Figure 5 (a) is the quality loss function over p (same positions as in Figure 1 (b)) and the formerly described core distance d. Figure 5 (b,c) display the sensitivities of both input parameters with respect to the quality loss. We observe the following aspects:

- a global trend of quality loss in positive d-direction (Figure 5 (a))
- a wave character in p-direction, which is usually undesirable (Figure 5 (a))
- zero values of the sensitivities, which help to identify minima or maxima of the quality loss function (Figure 5 (b,c))
- large sensitivities, which indicate great impact to the quality loss when varying the corresponding parameter at this point.

As in the examples before it has to be said that results crucially depend on the analysts personal assessment decisions.

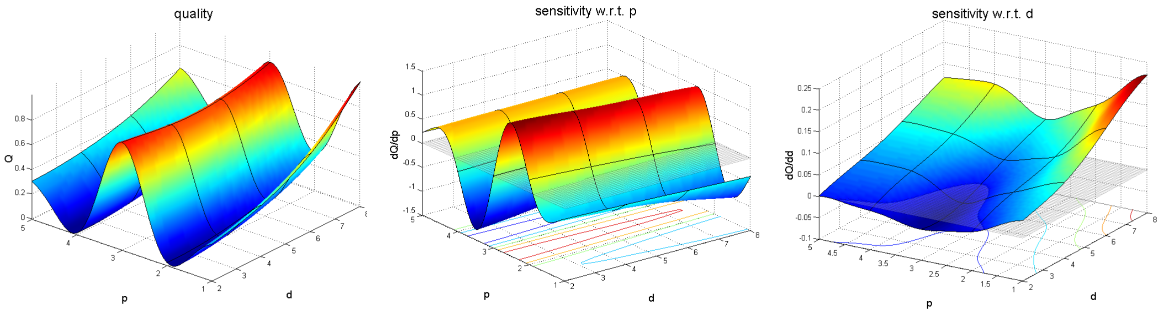

Figure 5: Quality (a) and sensitivity (b,c) over position p and distance d

CONCLUSIONS

Multidisciplinary Distributed Analysis and Design has been applied exemplarily to human comfort in combination with the static and geometric properties of a building section. The approach is computationally very demanding which presently limits the size of the design space and thus the range for practical applications. For problems where the response parameters can be computed by simplified models (not solving large-scale three-dimensional problems) this approach seems very promising.

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