PREDICTION OF INTERDISCIPLINARY CONSEQUENCES FOR DECISIONS IN AEC DESIGN PROCESSES

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EDITOR: P. Katranuschkov

Kai-Uwe Bletzinger, Prof. Dr.-Ing.
Technische Universität München
email: kub@bv.tum.de, http://www.st.bv.tum.de/content/people/bletzinger/vcard.html

André Lähr, Dipl.-Ing.
Technische Universität München
email: laehr@tum.de, http://www.st.bv.tum.de/content/people/laehr/vcard.html

***SUMMARY**: Consequences of a decision made by a planner (e.g. a project manager, or an engineer) within a collaborative planning process can hardly be foreseen. For example, such a collaborative scenario is represented by a planning process in AEC. In particular, during certain planning stages alternatives have to be considered which significantly influence the overall result. Todays AEC planning procedures can be very much improved by predicting simulation methods to judge about the quality impact of certain design or planning modifications. Also, proper interpretation of data is very important to give suitable insight into the characteristic consequences of individual planning decisions. This contribution presents an approach to achieve this goal by discussing needs, problems and implementation for the actual state of our research.*

***KEYWORDS**: sensitivity Analysis, distributed collaboration, agent technology, decision support, IFC.*

1. INTRODUCTION

Efficiency of a planning process is a prerequisite for the success of a product in AEC. Mistakes or suboptimal decisions can lead to severe negative influences on the ongoing planning process and, therefore, on the whole product quality. As a consequence, prediction of planning decisions would contribute to achieve a better result.

The idea of simulating the planning process is well known in aerospace and automotive industry. There are many techniques to support designers, which are already implemented. They are frequently used to apply multidisciplinary design optimization (MDO). However, in AEC most problems arise because of heterogeneity of the working environments of the planning participants. The most important difference is the lack of shared common product data models. Those models are being developed now (see section 2), but are not yet capable of keeping data consistently for a whole planning process in AEC. Another discrepancy is that in AEC there is hardly any discipline-spanning in-house-manufacturing. Different disciplines are distributed to various companies and, therefore, locations, which usually don’t work together for any longer than the duration of one planning project. Thus, the effort to adjust their systems for co-operation for every new project is usually too high to work economically. Lastly, in contrast to present work in MDO workflow management is a major topic for AEC. Many involved planning activities are very time consuming and are not fully automated. In particular, in the case of product modifications it is reasonable not to restart the planning process, but to find the process chain to incorporate the new setup correctly and consistently. This part gets even more important if we consider modifications during a planning process, which is common in AEC. Potential sources for mistakes or inefficiencies are not to consider all affected planners and not to find an economic workflow. Therefore, a dynamic workflow management is being developed to support this process.

An agent based communication environment allows flexible and scalable implementation of such a collaborative scenario. In this work, it encapsulates the integration of participating disciplines and their components as well as a dynamic workflow management. Furthermore, co-operation with existing agent communication systems is facilitated by using the FIPA standardized Agent Communication Language (FIPA-ACL) for message transfer.

For analysis of planning situations we apply methods from the field of sensitivity analysis, which are typically used in optimization disciplines (e.g. structural or topology optimization). They deal with the question how specific parameters of a system change if certain input parameters vary. Among others, Design of Experiments (DOE) and Response Surface Methods (RSM) are used. Applying these methods the level of impact (consequences) to particular planning parameters can be estimated, which arise by alteration of specified input parameters. Predominantly, this affects recurring parts of the whole planning process (e.g. dimensioning of constructional elements) if they are subject to multi-disciplinary involvement.

Communication with respect to data exchange is based on a shared common product model. A promising approach is the Industry Foundation Classes (IFC) because of its standardized data exchange methods (ISO 10303: STEP, SDAI). The potential amount of planner's applications supporting this exchange formats steadily increases.

2. RELATED WORK

Treatment of multidisciplinary and collaborative contexts has been a topic for many researchers in the past as well as today. With rising computational power computer support gets more and more important for research and industry. However, disciplinary interfaces and consistency of commonly used data are fundamental requirements for all approaches, especially when considering concurrent design activities. Several approaches in the field of concurrent design have been developed in the last years. SHARE is a project to support organization of design data among designer distributed in a network (Cutkosky & Tenenbaum, 1993). (Bliznakov et al., 1995) allows a monitoring of the workflow, so that designers can follow the actual state of the design. DICE offers a shared workspace for several designers to work on (Sriram & Logcher, 1993). A modularized approach was proposed by Pahng et al. by decomposing design problems and distributing them over a network.

These approaches have fixed relations between their modules and static workflow management. (Zhang & Xue, 2000) proposed a dynamic network handling. Participating nodes can be used automatically when an internet connection is established. An extension (Zhang & Xue, 2001) allows considering design alternatives using an AND/OR graph and finding the optimal design by optimization methods like genetic programming and particle swarm optimization.

The DFG (German Research Association) launched a priority program (SPP 1103, http://www.dfg-spp1103.de) in 2000, where several research projects are bundled and also contribute to this work. Mostly related to this work is the research from (Bilek & Hartmann, 2003). They developed an agent based approach to support collaborative work within AEC. Agents wrap proprietary software to enable communication. Also, the research of (Fahrig, 2004), (Romberg, 2003 and Romberg, 2004) and (Niggl, 2004), who worked on product model based simulation in computational fluid dynamics and computational structural mechanics is important for our research.

Furthermore, a MDO approach was presented by (Kim & Malone, 2004). Based on BLISS (Bi-Level Integrated System Synthesis) proposed by (Sobieszczanski-Sobieski et al., 1998) an MDO framework was developed using participating disciplines as BB (Black Boxes). Distribution and web deployment of MDO engineering processes is presented by (Woyak et al., 2004). Also, (Geyer & Rueckert, 2005) suggest a MDO concept in structural design of building by discipline composition and a static workflow management.

The International Alliance for Interoperability (http://www.iai-international.org/iai_international/) released IFC2x2 as the actual version in May 2003. This release has significant changes to the prior IFC2x version (e.g. the ST-4 extension for Structural Analysis Model and Steel Constructions – see http://cib.bau.tu-dresden.de/icss/structural_papers). However, currently there are only a few design applications that implement the actual version of the standard.

To serve business needs the product model has to be managed by model servers, which are capable of keeping consistency, multi-user access handling, etc. Among others, the EPM Technology Company (see http://www.epmtech.jotne.com/) is engaged in implementing these services. Their product, called EPM Data Manager, provides powerful functionality to handle EXPRESS based product models. Also, the Institute of Applied Computer Science in Civil Engineering at the University of Technology Dresden developed a model server along with the iCSS project (see http://cib.bau.tu-dresden.de/icss/) to fulfil the postulated needs.

Consistency and flexibility of product modelling is a very important factor for applying interdisciplinary product model based data communication. Usually, either individual objects or the whole model could be exported. The Institute of Applied Computer Science in Civil Engineering at TU Dresden developed a global model subset definition scheme (Weise et al. (2003)) to define partial models. It is capable of representing a specific view of the model (for example the structural model, or the HVAC model). This is one important step to support collaboration of planners from different disciplines.

Collaboration and co-operation in a planning process implies combining different planner's applications. Data transfer between them can be achieved by using and "understanding" the underlying common shared product model. Unfortunately, the number of planner applications implementing such product models, in particular IFC, is not very high. Most of them support read access from IFC only. Exceptions are, among few others, mainly CAD-applications like ArchiCad (see http://www.graphisoft.de/) or ADT (see http://www.autodesk.com) which produce IFC data in form of a STEP Physical File (ISO 10303-21 IS 1994). However, they usually support the geometric model only.

3. COLLABORATIVE ENVIRONMENT

3.1 General

As mentioned in section 2 several projects are dealing or dealt with environments for collaborative work in AEC. However, we develop our own model because we need additional features like dynamic workflow management or analyzing support for certain parts of a planning process.

A collaborative environment (CE) in our context needs to be capable to include workflow, involved planners and underlying product model data for a certain scenario. A scenario is set up by an analyst who defines the possible changes of product model data (variants). Afterwards, affected planners have to process this information and provide the CE with their results. Lastly, the analyst will pick up the data and do an analysis of that process resulting in an assessment of consequences and pointing out alternatives for the accomplished modifications.

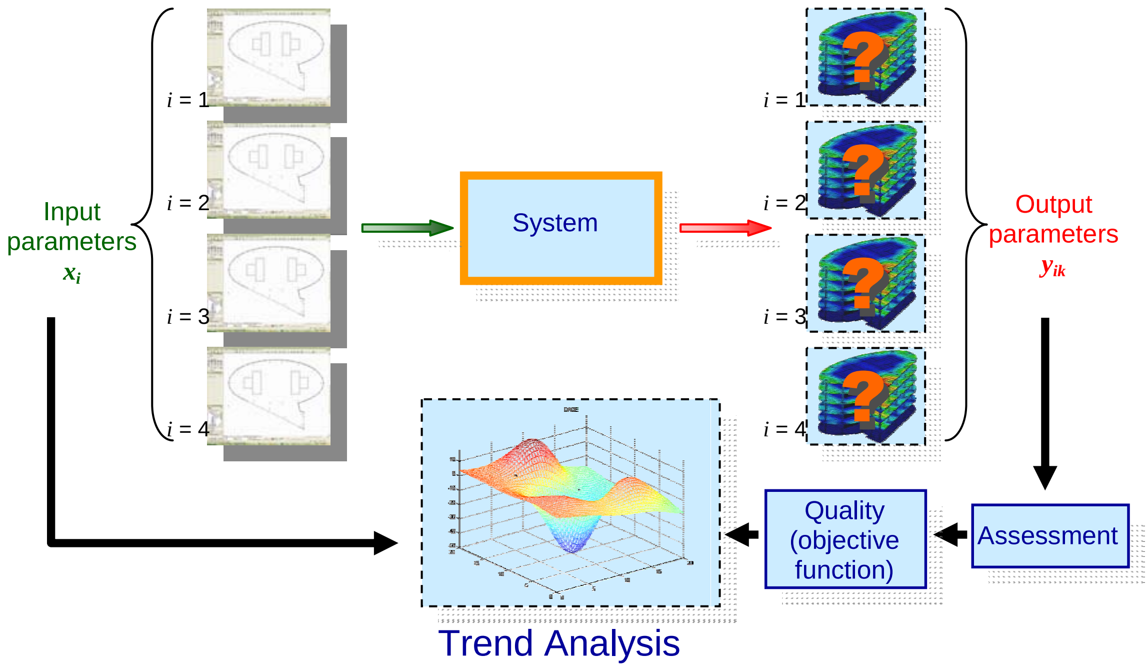


FIG. 1: System analysis

In Fig. 1 an overview of the analyzing procedure is depicted. In- and output of the system consists of several variants (i) and are the basis for an analysis, which is called Trend Analysis (see section 4). The CE is encapsulated in the System and treated as a black box from the view of the analyst, where only input parameters can be modified.

Heterogeneity and different demands of planner applications make generic interfaces highly essential. Therefore, development of an integration mechanism for involved planners is necessary. Furthermore, workflow management should not be handled statically by the analyst himself. A more dynamic workflow as well as product data management model has to be introduced.

In the following the “System” depicted in Fig. 1 will be revealed as an agent based CE, which possesses all the postulated properties.

3.2 Agent Technology

Agent technology is a methodology for handling network communication on a very high level of abstraction. A software agent is an independent computer program, which is able to autonomously interact with its environment. Decisions to be made are based on its perceptions and contribute to reach its goal. For detailed information see (Woolbridge and Jennings, 1995) and (Ferber, 1999). Furthermore, agent mobility is an important feature in our context. It enables an agent to migrate to other environments. Actually, agents are created on an agent platform, which can be spanned over several computers connected via network. The agent environments on these computers are called containers. Two types of agent mobility can be specified. Intra-platform mobility, which means migrating from one container to another within the same platform and inter-platform mobility for cross platform migration. In foreign containers agents are able to communicate and interact with agents and services residing there. The instrument of conversation is the agent communication language (ACL), a standard released by the Foundation for Intelligent Physical Agents (http://www.fipa.org/).

So called multi agent systems (MAS) conglomerate several agent platforms and allow the agents to move to other platforms (inter-platform mobility). Such agents are called mobile agents and strongly support collaboration of geographically distributed planners.

The implementation concerning the CE is completely done in the programming language Java. For agent support we use JADE (Java Agent Development Environment, http://jade.tilab.com/). All developed agents are derived from the basic Agent class *jade.core.Agent* of JADE.

3.3 Integration Mechanism

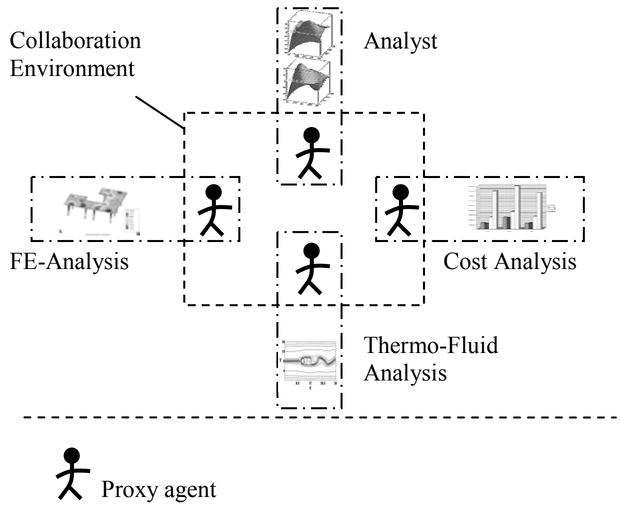


FIG. 2: Integration mechanism realized with “Proxy Agents”.

To integrate the different involved persons (planners and analyst) the class of proxy agents is introduced. A proxy agent (PA) represents the participating person or institution within the agent environment (multi agent system). Accordingly, a PA has to act as an interface to external, planner specific software, which mostly has been approved over a long time. This technique is also known as software wrapping. A software wrapper is a thin software program or module that converts program-specific input and output operations into generic sets of commands that apply to a wide range of programs. Furthermore, a proxy agent is immobile and resides in a local container on the same computer as the software to be integrated. The local container is connected to the (main) platform and the proxy agent is able to interact with this environment.

Fig. 2 depicts the integration concept. The central rectangle (dotted line) represents the agent environment. Note that there is no distinction between agent container and platform when the term agent environment is used. The dot and dashed line describes a local container (e.g. a personal computer) and contains the proxy agent as well as the application to be integrated.

3.4 Workflow Management

Typically, complexity of a planning process in AEC renders determination of the planners affected by another planner's decision highly delicate. Since within this environment mainly partials of a planning process are to be defined, there is a designated internal workflow management.

There is one central workflow manager, who gets notified if an event happens that affects the workflow of a run. A run in this context is the process starting with initial definition of the product model data and ending when all results from the involved planners are provided to the CE's data management (see section 3.5).

The workflow manager is an immobile software agent. Furthermore, there is no direct communication between a workflow manager and a proxy manager, because there is no static process chain steered by a central institution. A more flexible and dynamic way is letting the planners choose when to contribute to the run. To realize this, another class of agents are introduced, the monitor agents. Monitor agents are mobile agents, which have an owner. As mobile agents they can migrate to the workflow manager's environment and attach themselves to it. They possess a filter to screen the workflow events of the workflow manager and, in case of interest, inform their owner (proxy agent), who can react on such events.

Every time the workflow manager gets an event notice, he delegates it to the attached monitor agents. Fig. 3 depicts the processing of such an incoming event notice. After delegation to the monitor agents the second monitor agent realizes an event of interest and contacts his owner (proxy agent). An event notice is sent by a proxy agent when any CE relevant activity finished. Also, the product model agent (see section 3.5) is able to initiate (fire) these events.

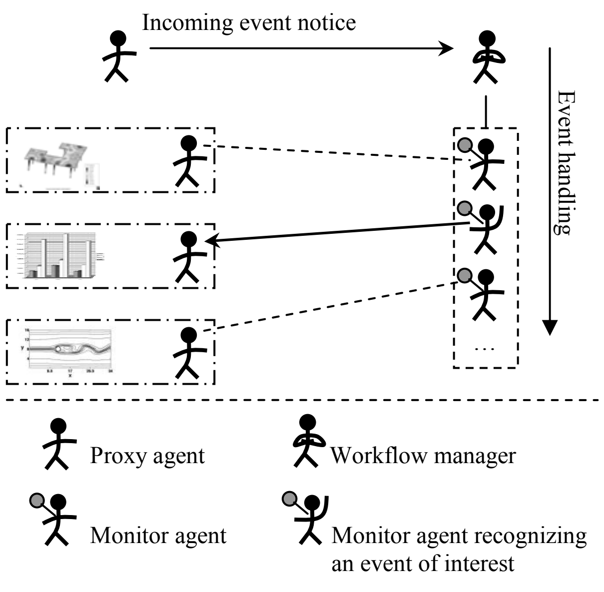


FIG. 3: Workflow management realized with "Monitor Agents".

The monitoring agent's behaviour is driven by filters. These have to be defined by a planner during setup of his local environment. Sharpness of these rules can significantly harm or decommission the workflow in CE. Currently, no restrictions are implemented and therefore planners are not completely free to set their filters. They can pick predetermined rules which guarantee CE workflow consistency. Up to now 3 filters are predefined:

Object changed:
This filter can be applied by specifying the GUID (globally unique identifier, see 3.5) of an element in the product model. It guarantees notification when this object is subject to a modification.

Model changed:
This also applies for a modification in the product model, but it does not matter which part is modified. The notification is done on every modification to the model data.

Planner activity started/ended:
When a planner wants to be notified on the work of another co-operation partner he can specify this filter. Additionally, he can choose if his monitor agent shall become active before or after a specific planner's activity.

Obviously, here is a big potential of exceptions like deadlocks. Infinite loops of two planners could occur that notify each other. Therefore, the workflow management system is provided with a monitoring feature for detecting those problems in advance. An underlying priority management (priorities of planners are defined by the analyst or CE admin) allows resolving the conflicts.

Currently, we are working on additional filters. Those described above are clearly not enough to describe a realistic process.

3.5 Product model management

The variety of data depends on the definition of the product model. We decided to implement the Industry Foundation Classes (IFC), maintained by the International Alliance for Interoperability because it is widely accepted in this field. Further developments, like the release of IFC2x3 in February 2006 seem to be a step forward to enable integration of the standard in current applications.

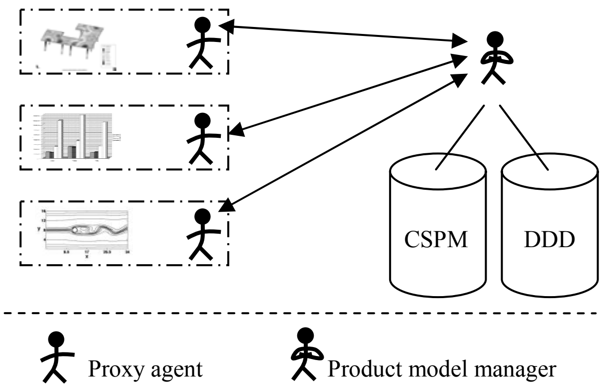


FIG. 4: Product model management.

Thus, planner application specific data may not be transferred along with the mentioned standardized product data model (IFC). Three reasons are responsible for this:

1. The product model definition is still under development and certain features are not available yet.
2. The planner specific data will not be part of the standardized model, because it is considered to be of no interest for other involved persons.
3. Planner applications may be unable to write their data back into the product data model consistently.

In particular, for our purpose, planner specific data may be very interesting indeed. This fact leads to the strategy to split the product data into two parts: A common shared product model (CSPM) based on IFC and an extension called dedicated domain data (DDD). If DDD cannot be expressed directly in IFC, it has to be converted to IFC Property Sets. IFC Property Sets are generic data containers, which can be attached to common IFC objects by a link to the globally unique ID (GUID).

The question is how to (i) transfer the data to the planner, (ii) modify it and (iii) merge it back to the product data model. Usually, a model server is responsible for accessing and keeping consistency of the global model. This task is fulfilled by a product model agent. The target applications, which will be used, must be able to read the data exchange format IFC as ISO 10303 Part 21 - Step Physical File (SPF) format to realize step (i). Clearly, step (ii) is left to the applications themselves and step (iii) again is to be managed by the product model agent.

A problem arises if DDD gets very large because of the variety or size of the result sets or the domain specific data. Transferring and parsing of such a file can easily lead to severe performance losses. The product model is able to filter corresponding DDD parts to keep exchanged data slim. This means that for every application/domain a certain subset of DDD data can be provided along with the CSPM.

A product model manager is in charge of handling the above mentioned aspects. It is implemented as a non-mobile agent.

4. TREND ANALYSIS

As already mentioned the variety of options for a designer (planner) has in a complex, multidisciplinary context is immense and mostly unmanageable. We define such a context as a system, which is influenced by several participating independent system designers. If we take into consideration that each designer can be a specialist in a certain field our system has to be able to handle multidisciplinary data as well as communication.

In this section we will discuss an approach for a system designer's decision support. We introduce the role of an analyst, who performs a system analysis, as replacement for system designer. If we transfer all that to AEC, it is thinkable that any person who can potentially influence our system can be an analyst. This can be a planner as well as a project manager. Our system in that case can encapsulate the planning procedure of a building project, for example. Clearly, the quality of an analysis depends on the accuracy of the system's model. However, knowledge of interdependencies of such models is very little, because of complexity. Therefore, we don't expect to get exceedingly accurate results. We aim at a coarser goal, namely the trends of the system behaviour for a specified design variety.

4.1 Sensitivity Analysis

Basically, sensitivity analysis is concerned with the question of how response y of a system varies, due to an alteration of the input parameters x.

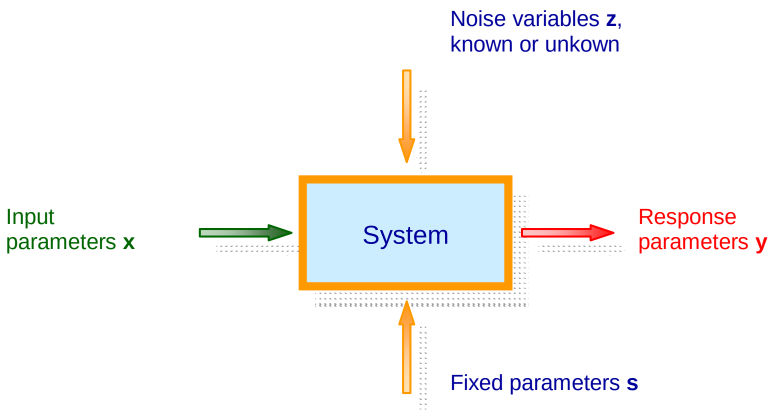


FIG. 5: Sensitivity analysis.

For completeness in Fig 5: additional parameters s and z are depicted. Noise variables z are non-influenceable, like uncertainties, etc. Fixed parameters s are parameters, which remain the same during the whole analysis.

Reasonability of a sensitivity analysis depends on the knowledge of the underlying system. Thus, it can be used to identify an unknown or predict the response of a sufficiently acquainted system.

Particularly, there is to be distinguished between screening methods, local and global methods. Screening methods are used to identify significant system parameters. One of the simplest applications of screening methods is the one-at-a-time (OAT) method. Their major limitation is the neglecting of parameter interaction (Saltelli et al., 2000). Local sensitivities of a system are imagined at best as partial derivatives with respect to the input parameters. The system has to be known as a function to directly derive the sensitivities from. Otherwise, methods like finite-difference approximation support obtaining the slopes of the calculated system. Considering "real" systems, an analyst is faced with the influence of noise variables. They are uncertainties, like measurement errors, rounding errors, etc., and can't be controlled directly. Therefore, global methods of the sensitivity analysis are applied to cover the total scope of input parameters. The goal remains the same, namely to analyze the system alteration by variation of input parameters.

4.2 Surrogate Models

In AEC sometimes a planner's task means high time and effort costs, in particular when testing various scenarios with different input parameters. To reduce this effort surrogate models can be created, which processing costs are significantly cheaper than the original ones. Generally, the model cannot represent the real planner's contribution exactly. This is to be faced with the crucial reduction of complexity and effort. The derivation of a surrogate model is realized by applying statistical approximation methods like Kriging to the response data of the tested planner's task. Kriging is a procedure with a statistical, interpolative character and was originally developed by Sacks et al. and presented in (Sacks et al., 1989). Further approximation methods are being examined at the moment.

Starting from certain system information and educing to corresponding function behaviour of significant input parameters is a task for Response Surface Methods (RSM). For example, supported by regression analysis, mostly linear or quadratic approximation is used. Furthermore, by application of Kriging these approximations are supplemented by a random process, which allows exact function values at the input sampling points. Aforementioned system information may be of experimental or numerical nature.

4.3 Design of experiments

DOE is a methodology to choose the location of the sampling points, used to accomplish statistical experiments. To make an expedient statement of a statistically derived model a certain number of experiments is to be processed. This number can be controlled and reduced by using different designs like e.g. full factorial, fractional factorial designs as well as Latin hypercube sampling (Box and Draper, 1987, Taguchi, 1986).

4.4 I/O-Strategy

As already mentioned in multidisciplinary environments a designer has mostly limited or no knowledge about foreign disciplines. In our environment such a designer takes the role of the analyst. Thus, we suppose the analyst has completely no idea how the system answer will look like if he changes some parameters. So, the question arises where to start and what about the magnitude of change. Generally, there are two strategies he could embark, which both have different pros and contras. Hence, a hybrid strategy is introduced to combine as many pros as possible.

All presented strategies will be explained based on a three dimensional system design space. It is set up by two input parameters x_1, x_2 and one system response Y.

4.4.1 Trial and error strategy

The analyst starts from scratch (Fig. 6:a) and chooses a system configuration that seems feasible for him. After a system computation he obtains a result (Fig. 6:b). By changing some input parameters he may get a different result from another system computation (Fig. 6:c). Comparing both results using the finite difference method, he gets information about how the result changed and the contribution level of the input parameters.

Based on this gathered information he can define a new system configuration by extrapolation or by hand after examining the results (see Fig. 6:d and Fig. 6:e). He may decide to stop the system analysis when he obtains satisfying data.

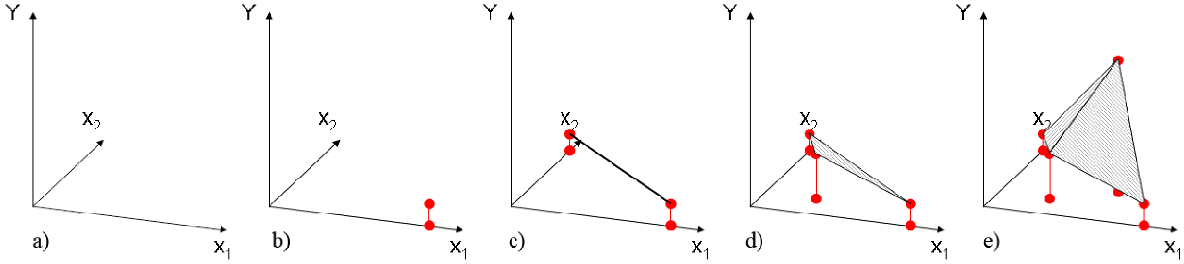


FIG. 6: Trial & Error strategy.

Pros:

- direct control and awareness of variants
- engineering experience of the analyst can be applied

Cons:

- interpretation of a high-dimension design space is very complex
- many user (analyst) interaction during analysis

4.4.2 DoE-Strategy

By use of DoE-Strategy, methods of the above mentioned field of Design of Experiments are applied. Several DoE-designs are thinkable. Again, starting from scratch (Fig. 7:a) the analyst has now to configure certain parameters depending on the corresponding design. This will lead to a certain grid pattern (Fig. 7:b). A system computation for every system design point yields a result for every system configuration (Fig. 7c). Based on this data a surrogate model is approximated and represents the system behaviour for the defined ranges of the input parameters (Fig. 7d). Depending on the single system computation time this can be very time consuming.

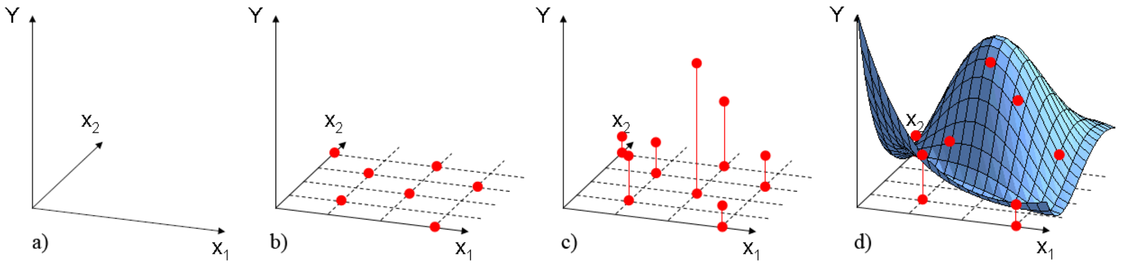


FIG. 7: DoE-Strategy.

Pros:

- achievement of a system behaviour in a defined system design space
- very few user interactions during analysis

Cons:

- interpretation of a high-dimension design space is very complex
- no user interaction possible during analysis → computation of potentially irrelevant system design points → high computation time

4.4.3 Hybrid DoE supported interactive strategy

This strategy tries to combine both aforementioned procedures. The DoE-strategy is condensed to very simple and comprehensive designs. Firstly, this reduces the knowledge of the analyst about these statistical methods, which is usually very irritating for users taking the role of the analyst. Secondly, it turned out that coarse information of the system design space is sufficient very often. If necessary, refinement can be done after this coarse information is available.

Compared to the “trial and error”-strategy (Fig. 6) the hybrid approach supports the analyst at Fig 8.a and Fig 8.c by suggesting a new design point (Fig. 8:b and Fig. 8:d) that could most probably reveal much information about the system. User interaction is possible after each design support, so the analyst can decide whether to accept the suggested point or to choose another one. Again he ends up with a model of the system behaviour as an approximated surrogate model (see 4.2).

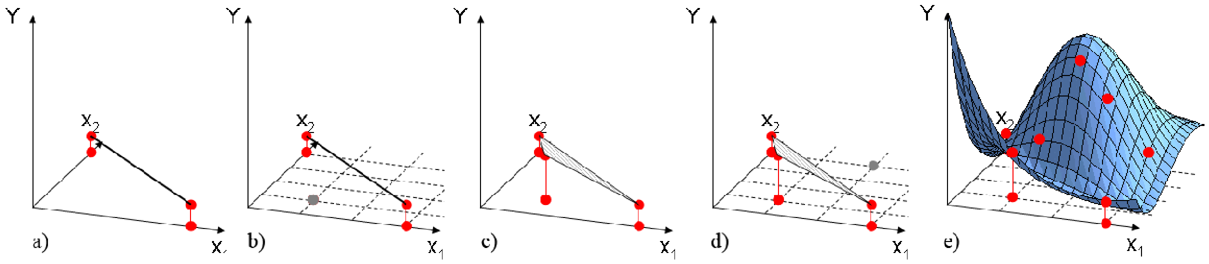


FIG. 8: DoE supported interactive strategy.

4.5 Assessment

When monitoring a system in a multidisciplinary context the question arises how to assess results. Usually, more than a single response parameter (RP) will change on varying system input. Similarly, boundaries or constraints of certain RPs have to be regarded.

We realized system behaviour assessment by introducing *preference functions* (PF) and weighting. Application of PFs results in a dimensionless quantity defined as *quality* for each RP. This can be seen as normalized scaling and allows combination of several RPs based on weighted summation.

PFs are operators acting on RPs. They can take any evaluable form. Actually, an analyst is free to choose any PF. Due to clarity a set of PF classes are defined, which can be applied to RPs. Up to now there are three basic classes :

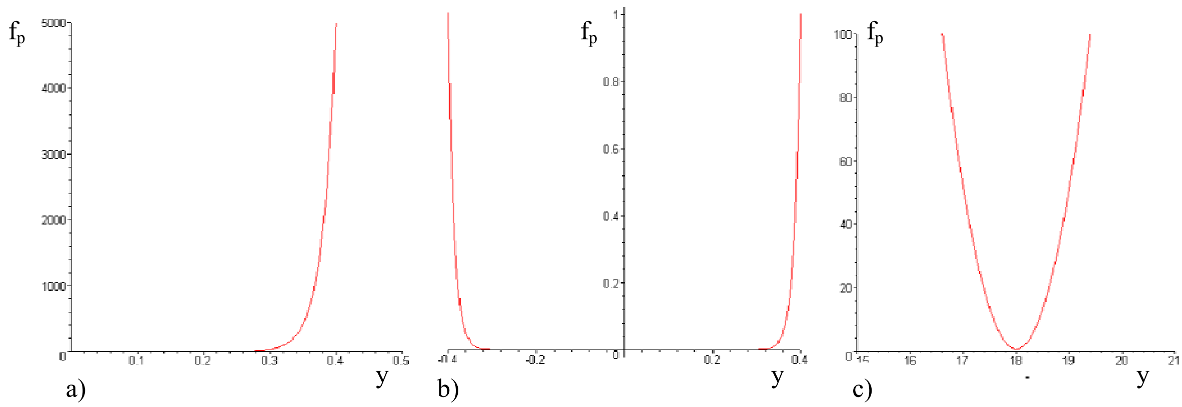


FIG. 9: Preference functions.

- one sided boundary class (OBC) → $f_p = e^{a(y-b)}$ (FIG. 9a)
- two sided boundary class (TBC) → $f_p = e^{a(-y-b)} + e^{c(y-d)}$ (FIG. 9b)
- optimal value class (OVC), → $f_p = ay^2 + by + c$ (FIG. 9c)

The configuration parameters used above (a,b,c,d) are calculated from specific information obtained from the user (feasible region, boundaries, optima, etc.).

A digital boundary class may be an appropriate candidate for an extension here. This and other classes will be addressed to further developments of this framework.

Although PFs are normalized and dimensionless compared to the related RPs their absolute values may differ very much among each other, as demonstrated in Fig. 9. That is in particularly true for sided boundaries where the PFs are activated within a small transition zone.

As mentioned above, PFs transform RP values to a *quality loss*. They yield low values for good quality and vice versa. It can be said that they prefer feasible or acceptable RP values by converting them to low PF values.

Finally, an explicit weighting can be applied by introducing a weighting parameter g for every RP.

$$Q(\overline{X}) = f(g, f_p, y(\overline{X})) \qquad (1)$$

In (1) a general expression for an assessed and weighted quality loss Q is presented with respect to a system configuration $\overline{X}$. The index k runs from 1 to m, which is the number of RPs (y_k.). In section 5 the derivation of Q is described in detail.

4.6 Quality Analysis

A quality analysis in this context means the overall result of a system analysis, including several system computations. In section 4.4 the term of design space was already mentioned. Thus, a solution is always expressed in a n-dimensional design space, where n depends directly on the number of system parameters (input and response parameters). For a demonstrative explanation we chose 2 input variables x_1, x_2 and the system quality loss Q. Consequently we get a 2-dimensional system design space for the results.

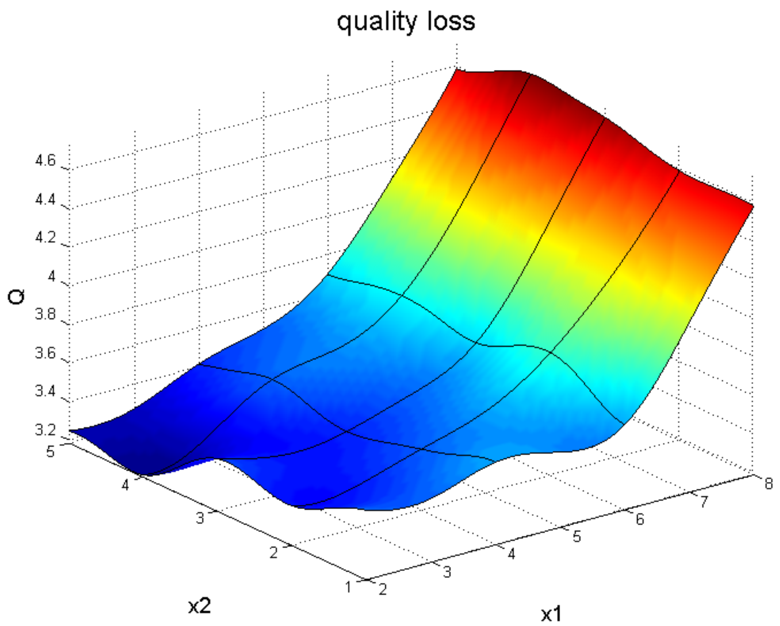


FIG. 10: Quality loss Q over x_1 and x_2.

In Fig. 10 the approximated surrogate model of the overall system quality loss function Q is shown. It is composed from the individual quality loss functions which in turn are related to the system response y as functions of the design parameter x_i. Lower quantities of the quality loss Q indicate more preferable solutions including conflicting objectives and constraints. The surrogate model gives an overview of the problem and allows for an assessment of the evaluated design space as well as for identification of interesting “unknown” regions. The analyst may decide if it’s worth to explore these regions or to get a new idea for another system configuration and to further improve his experience.

When exploring the design space observation of the sensitivity (partial derivative) of the solution with respect to input parameters at specified design points may be very interesting. For example, the magnitude of the result’s dependence from the input parameters or possible extrema w.r.t. these parameters can be evaluated.

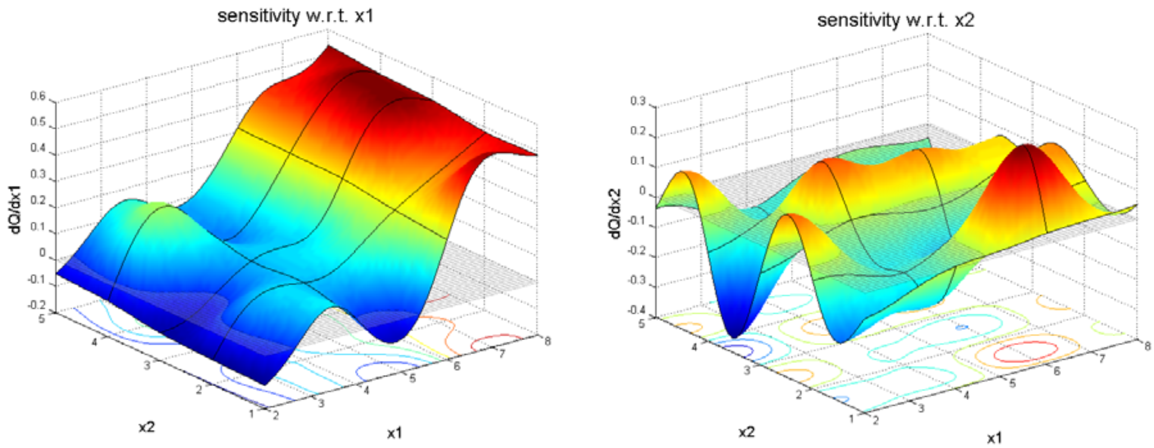


FIG. 11: Sensitivities $\partial Q/\partial x_1$ and $\partial Q/\partial x_2$

Sensitivity is computed as the partial derivation of the quality regarding to the input parameter. Fig. 11 shows the sensitivities of the quality loss *Q*. Additionally, a zero plane, indicating robust system configurations and the iso-lines for sensitivity are shown.

5. EXAMPLE

In this section an example of an analysis will be presented. The participating disciplines for this scenario are structural analysis and thermo-fluid analysis. Former is represented by an application from Institute of Computer Science in Civil Engineering at the Technical University Munich (Romberg, 2003) and the latter is a computer code of the Institute of Computer applications in Civil Engineering at the Technical University of Braunschweig (Germany). The example arises from a cooperation of our research projects within the DFG priority program 1103.

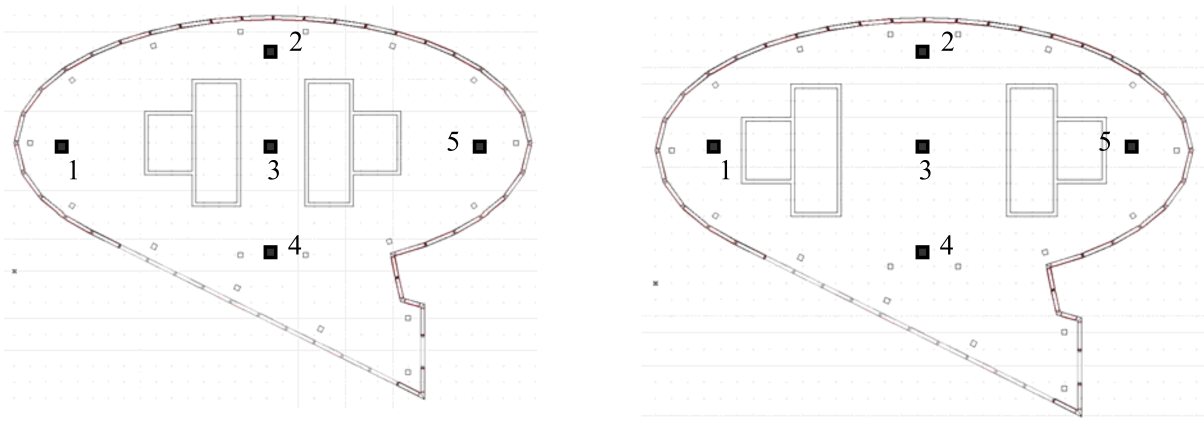


FIG. 12: Floor plan. Two variants with different distances between the stairways and locations for the measure points p1..p5.

Depicted in Fig. 12 is a floor plan of an office storey. It is to be analyzed how the distance between the stairways is correlated with (a) the room climate at several measuring points and (b) the maximum deflection of the ground floor. The result of this analysis will be an idea of a beneficial distance between the stairways with respect to a well suited combination of (a) and (b). Furthermore, locations with good climatic conditions shall be estimated.

At first, several (*n*) variants of product models (system configurations) are created by the analyst and provided to a common product model management by using the collaborative environment, described in section 3. The participating planners calculate each variant and send their results back to the CE (system computation). Afterwards, the analyst has access to all results of all variants and can begin with the analysis by defining input and output parameters. Input parameters $\overline{X}_i$ for this case are the distance of the stairways (x_{i1}) and the position of the measure points (x_{i2}), where

$$\overline{X}_i = [x_{i1}, x_{i2}, ..., x_{ik}, ..., x_{in}],\ i = 1..n, k = 1..m \quad (2)$$

and m is the number of input parameters of a scenario.

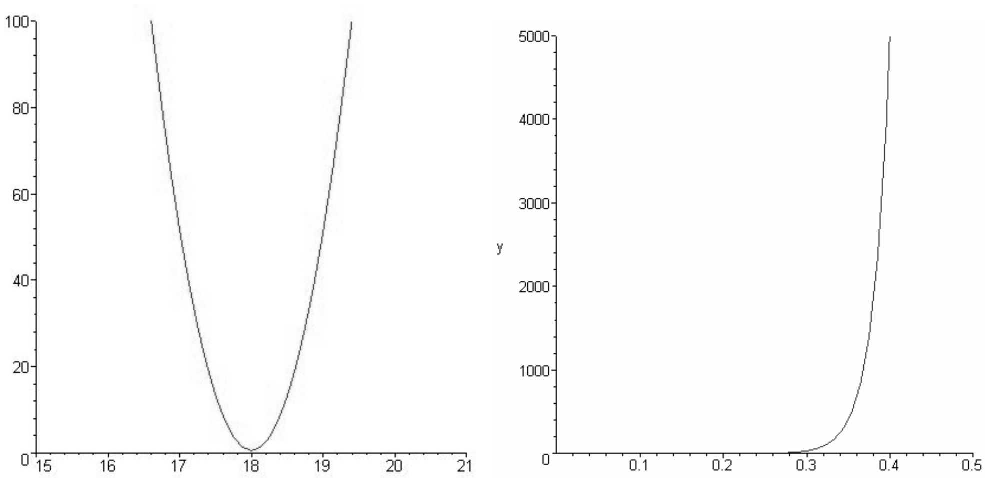
The maximum deflection of a base plate (y_{i1}), air temperatures (y_{i2}) and velocities (y_{i3}) at the measure points pos_q (q = 1..5) are treated as the output parameters of the system configuration i.

As explained in section 4.5 response parameters for each run are combined to one single system response Q_i for each system configuration i, where

$$Q_i(\overline{X}_i) = \sum_{j=1}^{r} f(y_{ij}(\overline{X}_i)),\ j = 1..r \quad (3)$$

and r refers to the number of response parameters (r = 3 in this case).

The summation in (3) claims that these response parameters have to be scaled and weighted. Scaling is done by preference functions f_p, which penalize their target for deviation from the considered individual optimum values or exceeding of critical borders by yielding high values (see 4.5).



$$f_{pj} = ay_{ij}^2 + by_{ij} + c \qquad f_{pj} = e^{a(y_{ij}-b)}$$

FIG. 13: Preference functions.

Depicted in Fig. 13 are two preference functions. On the left hand side a parabolic one, which filters for an optimal value y_i = 18°C (OVC, see section 4.5) and on the right hand side an exponential one (OBC, see section 4.5), which filters out values beyond a critical border of y_i = 0.4cm. The corresponding parameters (a,b,c) for the preference functions are calculated automatically after definition of the optimum or border value and a preference factor. The latter describes how rigorous borders or optima are preferred (steepness of the preference functions).

Typically, an analyst needs to assign the importance of single response parameters. This is realized by weighting parameters like g_r in the following:

$$Q_i(\overline{X}_i) = \sum_{j=1}^{r} g_j \, f_{pj}(y_{ij}(\overline{X}_i)) \tag{4}$$

After application of preference functions f_{pj} and weighting factors g_j we obtain dimensionless values Q_i, which are treated as a measure for quality loss. Clearly, this quality depends on the choice of preference and weighting functions and is therefore an individual assessment of the analyst. Due to the definition of the preference function (see section 4.5) low quality loss denotes good quality circumstances and vice versa.

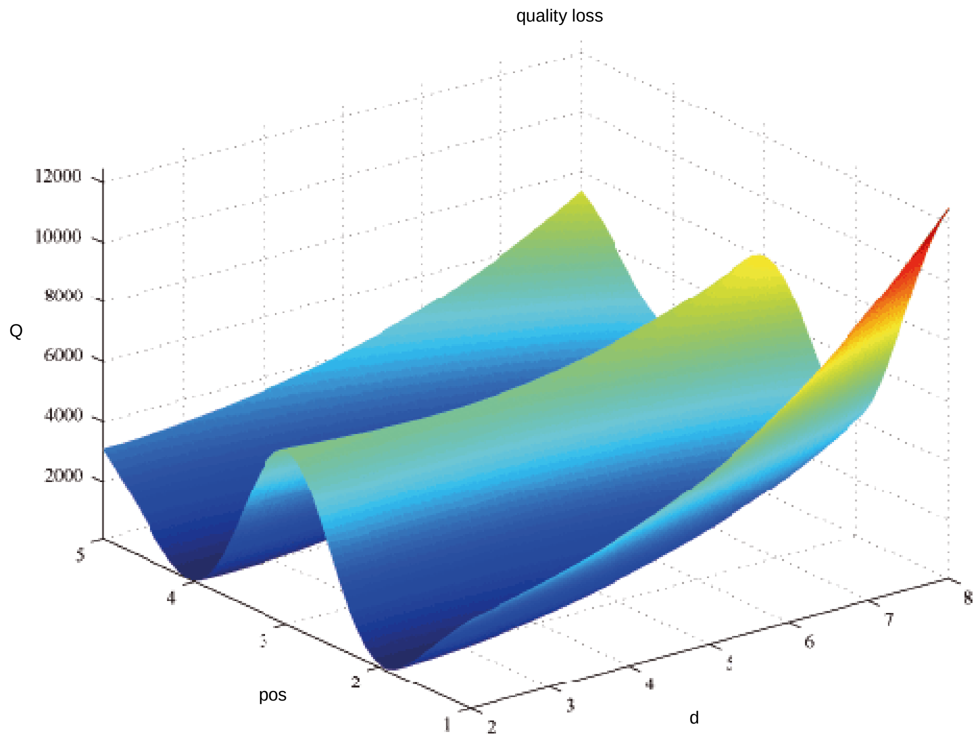


FIG. 14: Quality loss over d and pos.

Next, the analyst defines his design space, spanned by input parameters $\overline{X}_i$ and the response Q_i. Overall, we have $n_i \bullet n_{pos} = 20$ grid points with discrete values. They allow the approximation of a response surface. Depicted in Fig. 14 is the resulting surface obtained by application of the Kriging method.

Fig. 14 displays parameter combinations which are beneficial (low values) with respect to our quality loss definition, as well as unfavourable. Some observations can be done directly out of this diagram:

- A global trend, where quality gets worse the larger the distance of the stairways gets.
- At measure point 3 there constantly is a disadvantageous quality

Sensitivities of the input parameters $\overline{X}_i$ give even more information. They are partial derivatives of the quality with respect to the input parameters. Fig. 15 displays the sensitivity of the stairway distance *d* and the measure point location *pos*.

The most obvious observation here is that in the area around *pos* = 1 and *d* = 8m the sensitivity of *d* is very high. This means that a modification of *d* at this input parameter combination will lead to significant changes of the quality. Thus, an analyst may identify areas where a great amount of improvement can be easily achieved.

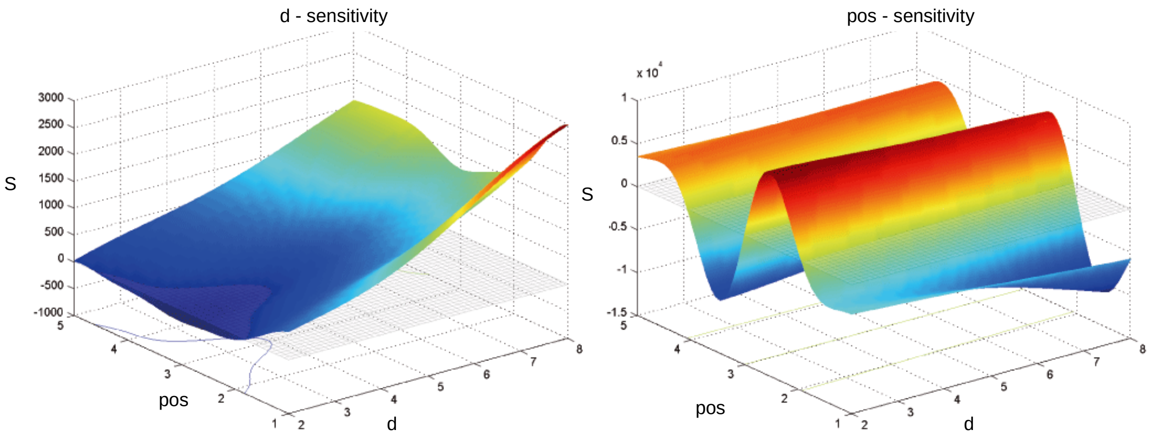


FIG. 15: Sensitivity of d and sensitivity pos.

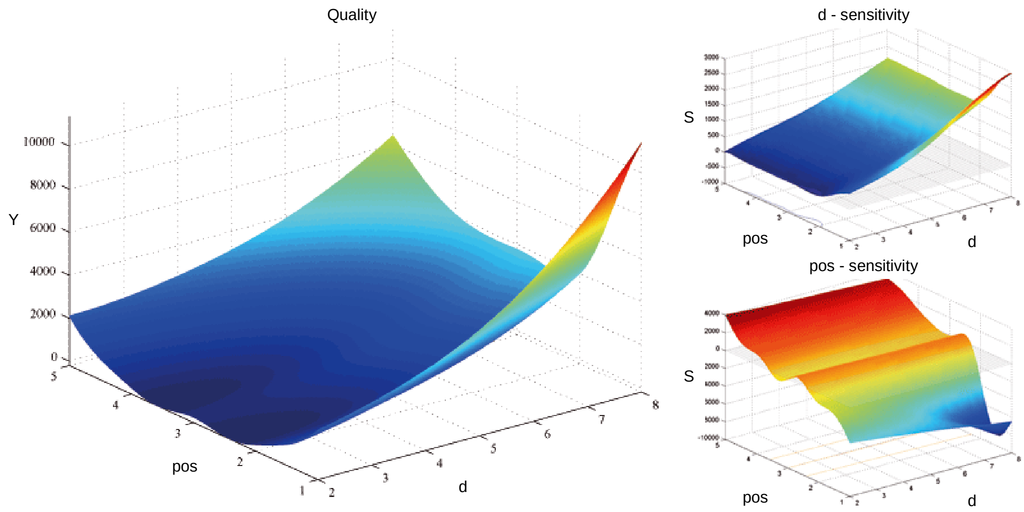


FIG. 16: Quality loss over d and pos without influence of climate conditions and sensitivities.

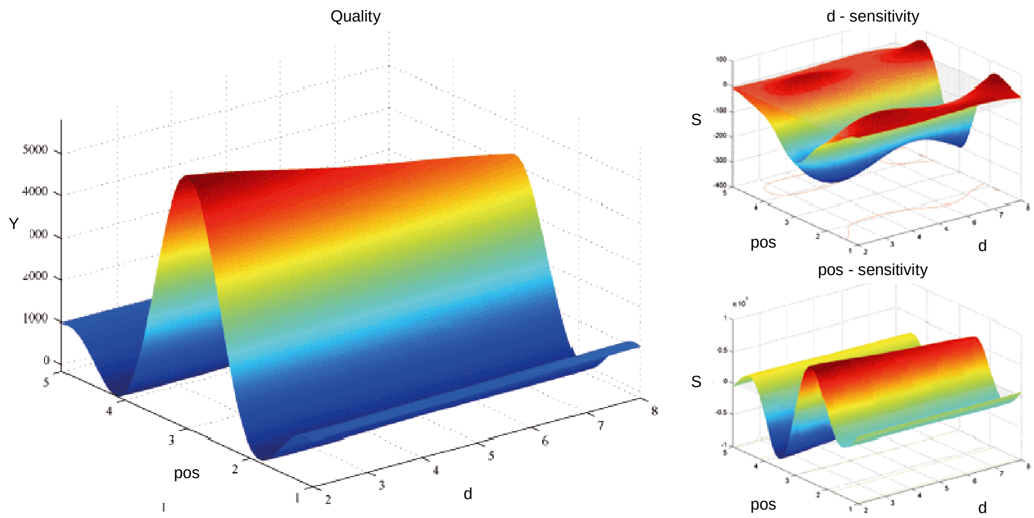


FIG. 17: Quality loss over d and pos for climatic quality and sensitivities.

An interesting observation can be made if the climate conditions are filtered by varying the weighting parameters out and we look on the quality loss of *d* only.

In Fig. 16 we can see that the disadvantageous circumstances must be caused by the climatic conditions. Displayed in Fig. 17 is the climatic quality, constituted of air velocity and air temperature.

Additionally, we find that the climatic quality at p=3 gets worse the closer d is, which is a contradiction to the global trend (Fig. 14) and may lead to a further examination.

Thus, it can be seen that the analyst has various possibilities of analyzing and assessing certain scenarios.

6. CONCLUSIONS

An analysis method was presented to support planning decisions on basis of trend analysis in a heterogeneous planning environment in structural engineering.

Still, product model data management is a difficult problem. Since almost no applications support the check-in of their local data to a common shared product model, our above described DDD concept is used for this issue. For a manageable amount of different planner applications this is applicable, but beyond that the effort to keep track of the variable data format will become very high. Besides that, we seek cooperation with researchers of product model technology to develop a reliable solution for product model data transactions.

During the analysis a response surface is being approximated. Typically, many steps in a planning process in AEC cannot be made without human interaction. This limits the number of variants to be calculated. Thus, the amount of sampling points is relatively low and the approximation of a response surface may be relatively inaccurate. Otherwise, in many cases it is sufficient to get a coarse idea of system behaviour which may reveal new (better) alternatives.

The major benefits of this project are :

- analysis support & prediction of consequences
- dynamic workflow management

Prediction of consequences can be performed by an application of a trend analysis. Applied methods from the field of sensitivity analysis can be seen as a first step to MDO in AEC. However, adequate visualization concepts have to be developed to provide better understanding of the analysis' results to the analyst.

The dynamic workflow management allows a highly flexible composition of process chains within a planning process, in particular when modifying specific parameters. This contributes to avoid mistakes and inefficiencies, which emerge by creating incomplete alternative workflow variants. The most crucial factor is the definition of the rules driving the behaviour of the agents when events are received. If they are too strict the same mistakes as before can be made. On the other hand, if they are too soft, an overhead in efforts of the participating disciplines can be generated.

After finishing of implementation of the agent based collaboration environment our research concentrates on the analysis methods. Especially the human computer interaction shall be examined. Predominantly, this means to facilitate the usability for engineers or project managers, for example by linking the results to the visualization of a scenario.

Within the next year this method shall be tested and verified on some real case scenarios, especially within DFG funded priority program 1103.

7. ACKNOWLEDGEMENTS

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