International Conference on Adaptive Modeling and Simulation
ADMOS 2005
P. Díez and N.-E. Wiberg (Eds)
© CIMNE, Barcelona, 2005

FROM ADAPTIVITY TO COMPUTATIONAL STEERING: THE LONG WAY OF INTEGRATING NUMERICAL SIMULATION INTO ENGINEERING DESIGN PROCESSES

E. Rank, A. Borrmann, A. Düster, A. Niggl, V. Nübel, R. Romberg, D. Scholz, Ch. van Treeck, P. Wenisch
Lehrstuhl für Bauinformatik, TU München, Arcisstr. 21, D-80290 München

Key words: Adaptive Modeling, p-FEM, product models, computational steering

Summary. *This paper tries to 'draw the large picture' of integrating numerical simulation in a multi-disciplinary design process: Starting from a generic model of a technical product, different domain specific models will be derived. As practical examples structural analysis as one domain and HVAC (heat, ventilation, air conditioning) as another will be considered. Within these domains different concepts of collaboration support will be discussed. In structural simulation asynchronous collaboration using error and model adaptivity will be investigated. The suggested numerical method is based on high order finite elements and on a strictly volume-oriented discretization of solids and thin-walled structures. HVAC simulation, on the other hand, will be integrated into a computational steering environment supporting synchronous collaboration of engineers working at the same time on one common model within their individual virtual reality environment and using 'online' CFD-simulation.*

1 ADAPTIVE P-FEM FOR NON-LINEAR PROBLEMS

Since the first publications on adaptive simulation procedures in the 1970s numerous achievements have been obtained especially concerning the finite element analysis: A posteriori error estimation is the basis for quality control using h-, p- or hp-extensions [1,2]. Applications of adaptive finite element analysis range from structural computations and computational fluid dynamics to multi-field and multi-scale simulation [3-7]. Figure 1 shows an example of an elasto-plastic computation using the p-version of the finite element method. It takes advantage of the hierarchical nature of the Ansatz spaces, allowing to immediately control the convergence of selected quantities of interest.

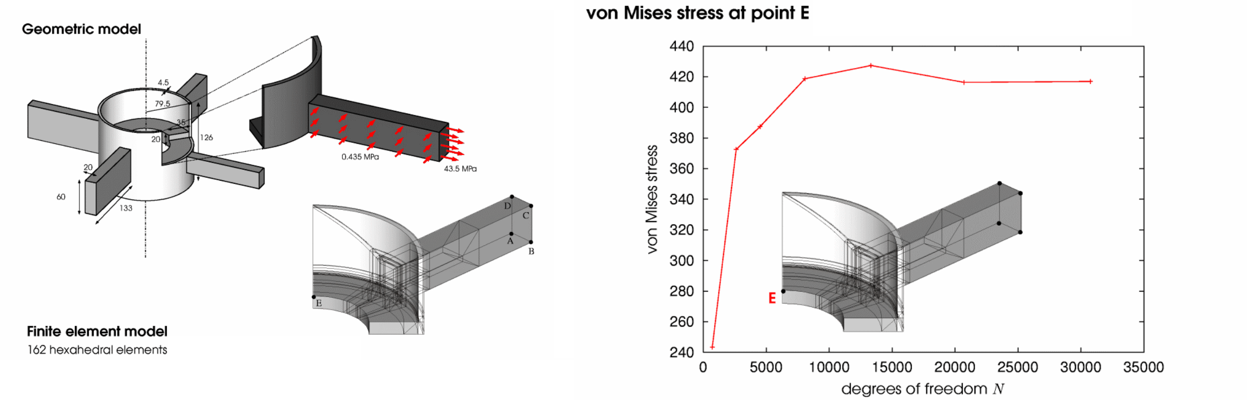


Figure 1: Elasto-plastic p-FEM computation

2 MODEL ADAPTIVITY

During the last 15 years first steps have been made to extend the control of the discretization error to an estimation and control of the modelling error [8]. These developments are based on the awareness that in general not only *one* model should be considered for the description of a physical process or product, but that a reliable numerical simulation should be based on a *sequence* or a hierarchy of more and more detailed mathematical models. P-FEM is again a powerful basis for controlling the modeling error. A typical model assumption being inherent e.g. in plate or shell theories is the polynomial degree of displacement components over the thickness of the structure. As p-FEM allows to select the polynomial degree of the approximation in any direction independently, the ‘model’ of a thin-walled structure corresponds to a chosen order in thickness direction, which even can be adjusted adaptively. An example is shown in Figure 2, where a hemispherical shell with a stiffener is computed with a sequence of adapting distributions of polynomial degree of the shape functions (see [9]). The p-degree over the thickness of the construction is plotted showing that in different parts different polynomial orders and in this sense different models are necessary for an accurate simulation.

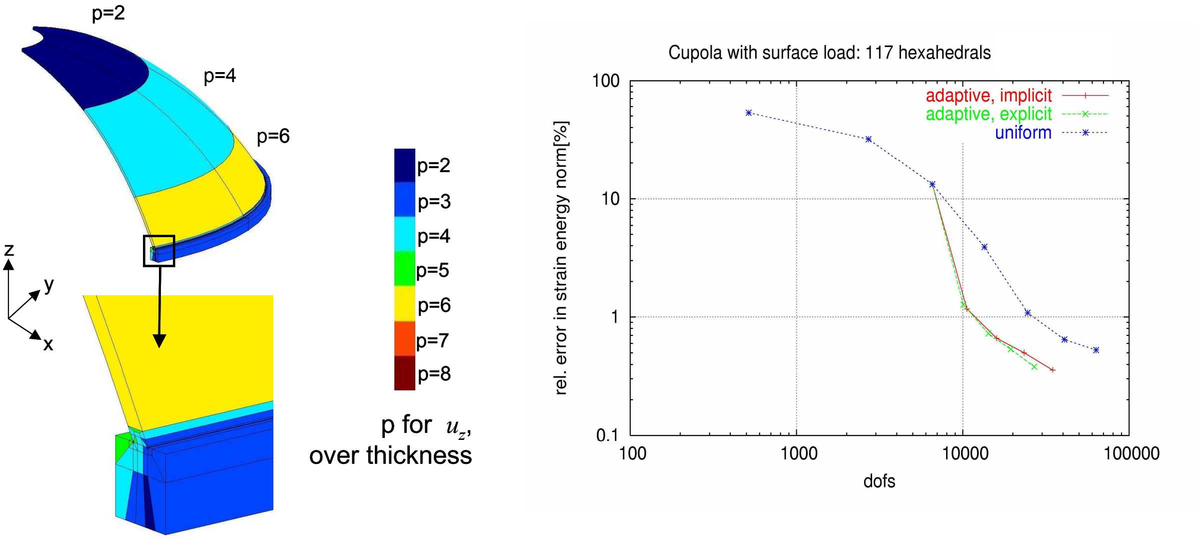
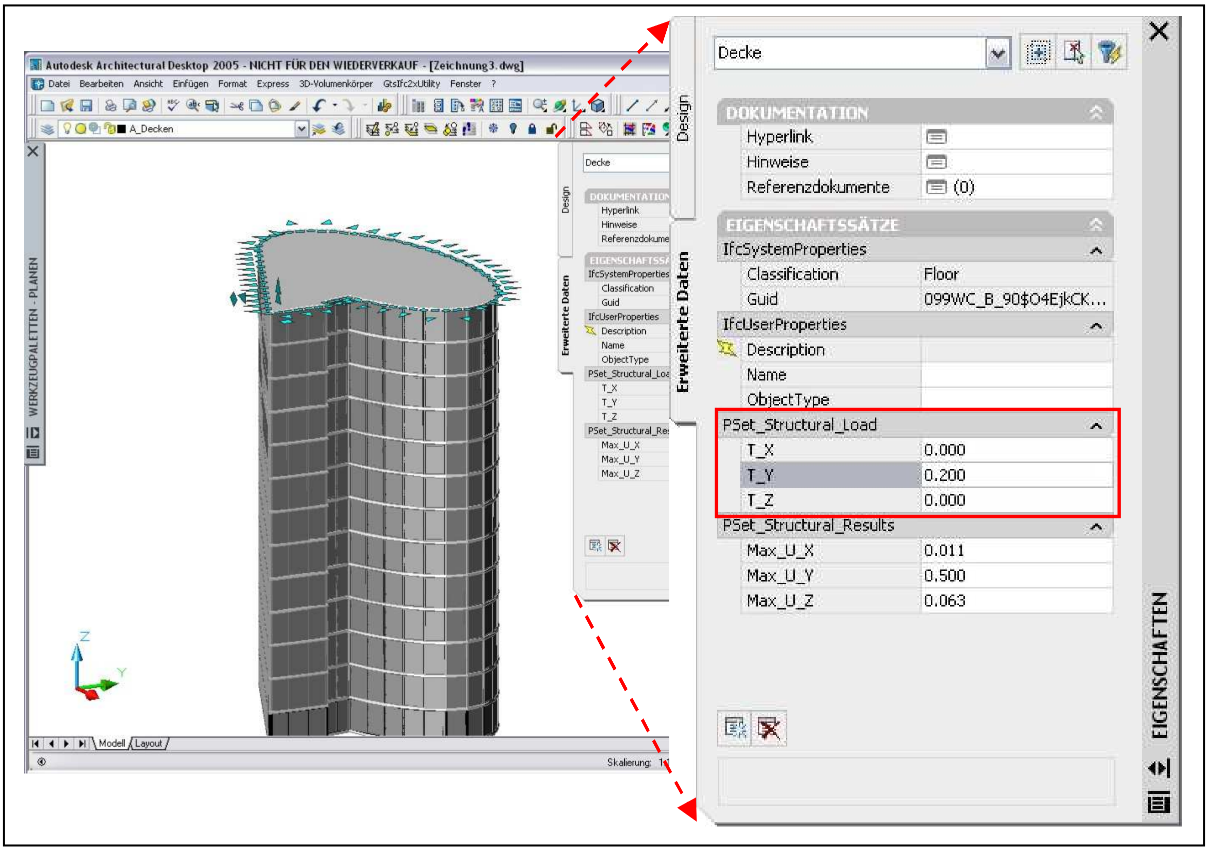


Figure 2: Model adaptivity: Adaptive selection of p-degree over thickness of cupola with convergence curve

3 PRODUCT MODELS

Virtually independent of these developments on adaptive numerical simulation many achievements have been obtained in applied computer science on the computer-based description of technical products and processes. Many of these developments have their roots in Computer Aided Design, yet extending these concepts by complex data base models and by the time domain to “n-dimensional” modelling systems. Figure 3 shows an example of a building product model which does not only store all material properties of the complex construction but also allows to define boundary conditions and loads directly associated to the geometric model.



Decke

DOKUMENTATION	
Hyperlink	
Hinweise	
Referenzdokumente	(0)
EIGENSCHAFTSSÄTZE	
IfcSystemProperties	
Classification	Floor
Guid	099WC_B_90$O4EjkCK...
IfcUserProperties	
Description	
Name	
ObjectType	
PSet_Structural_Load	
T_X	0.000
T_Y	0.200
T_Z	0.000
PSet_Structural_Results	
Max_U_X	0.011
Max_U_Y	0.500
Max_U_Z	0.063

Figure 3: Product model based definition of loads and boundary conditions

Building product models are typically based on a component-oriented description of the geometry. Components are ‘walls’, ‘openings’, ‘slabs’ or ‘columns’ being three-dimensional geometric objects yet often only with an *implicit* description of their geometric shape. Therefore, before a finite element analysis can be performed, a transformation to an *evaluated* geometric model has to be performed in a first step. A classical h-version finite element approach then requires *dimensional reduction* of the model (Figure 4, left), whereas a p-FEM approach can directly use the three-dimensional solid model (Figure 4, right) as a starting point for mesh generation.

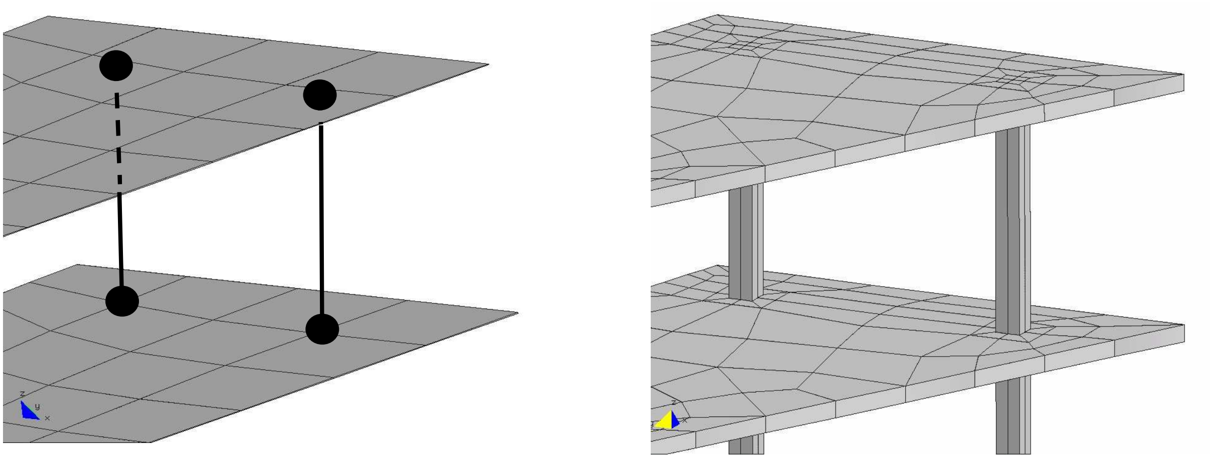


Figure 4: Dimensionally reduced model and solid model

Product models can now be embedded into a collaboration framework supporting cooperation of engineers and designers of the same or even of different application disciplines (Figure 5)

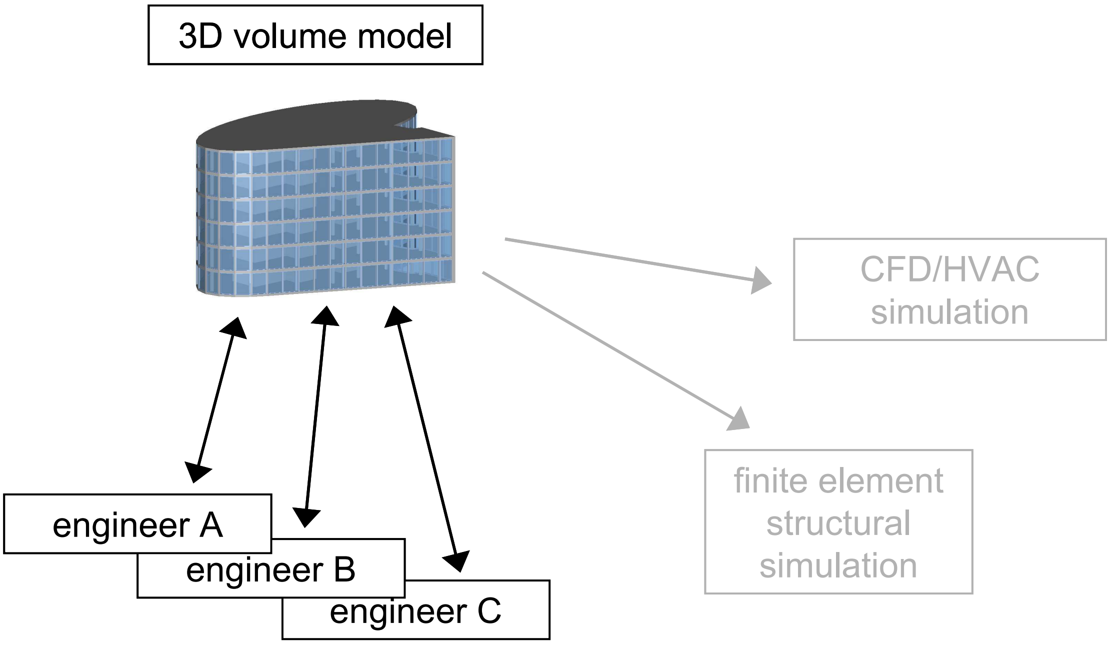


Figure 5: Collaboration supported by central building product model

According to [10], collaboration can be classified into synchronous and asynchronous collaboration. Whereas synchronous collaboration means that the participants work together at the same time, in asynchronous collaboration no explicit time coordination is imposed on the cooperative work. Whereas we have integrated structural simulation as discussed above into an asyncronous framework, we will now concentrate on syncronous collaboration and use as model application field HVAC-simulation (heat, ventilation, air conditioning, Figure 6). Our *computational steering* [11] approach allows multiple users to work at the *same time* on the *same numerical* model. *Online modifications* of the geometric model are possible and simulation results can be seen more or less *immediately* using specific interaction clients being available for each individual user. The numerical approach for the CFD-simulation used in this project is Lattice-Boltzmann (LB-)method, which is described in detail e.g. in [12-15] . Major advantages of this approach are the following:

- As Lattice-Boltzmann methods use cartesian computational grids, very efficient, octree-based generation techniques could be developed allowing an adaptation of the grid to modifications of the geometric model *on the fly,* i.e. during an ongoing simulation.
- The algorithmic structure of LB-methods is ideally suited to parallelization and vectorization and thus allows efficient simulation on high-performance computing facilities.

Figure 6. HVAC engineers taking part in a collaborative session using different human-machine interfaces.

4 THE ARCHITECTURE OF THE COLLABORATION PLATFORM

The collaborative system [16] was developed as a distributed multi-user application. Everyone participating in the collaborative session can work interactively with this application by means of an individually configurable human-machine interface.

This approach has two major advantages: On the one hand, the visual interface can range from desktop monitors to high-end visualization equipment, such as Virtual Reality environments. On the other hand, it enables each participant's viewing and interaction facilities to remain completely independent from each other (Figure 7). In this way, typical phenomena which are familiar from collaborative environments based on shared desktop or shared application approaches, like “mouse wars”, or sickness caused by remotely controlled viewing can be avoided.

The basic architecture of the conceived collaborative platform consists of the central collaborative server, an arbitrary number of simulation servers and an arbitrary number of clients.

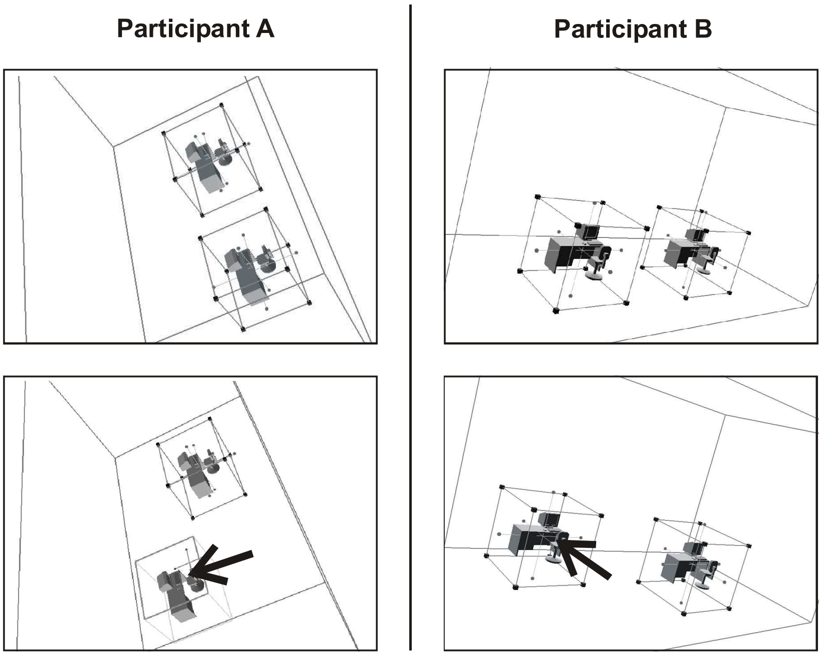


Figure 7. Independent views of two participants

Figure 8 shows these components and the communication paths between them. Each of the components can be run on different machines.

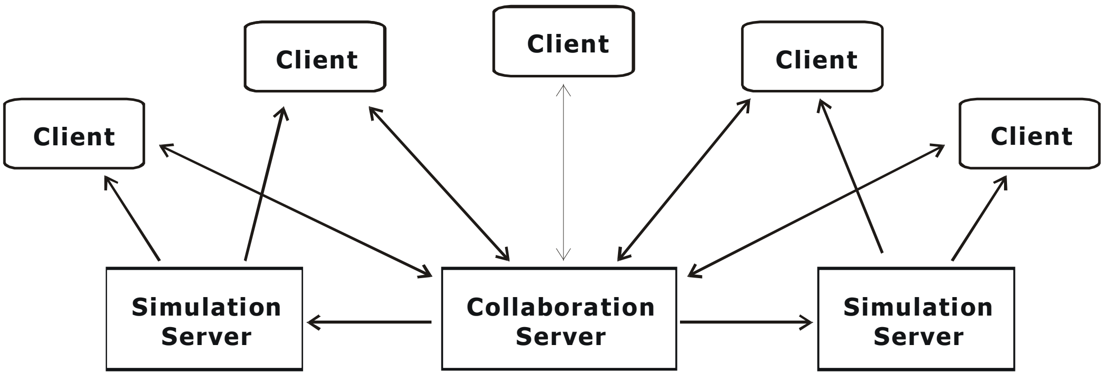


Figure 8. Overview of the multidisciplinary collaboration platform. Not every client has to receive simulation data and different clients can receive data from different simulation servers.

The collaboration server has to perform the following tasks:

- Management of users, their roles and rights
- Management of the common model
- Management of the audio conference

The core of the collaboration server is the model management module. A hybrid model joining the geometric and the semantic model is used. In our example, the model represents the obstacles in the fluid domain and the fluid domain hull.

Especially important are the acting boundary conditions, like the type of surface (slip or non-slip), the inflow velocities and the outflow pressures. These boundary conditions are managed as semantic data attached to geometric objects.

Modifications like adding, removing or transforming obstacles are communicated from the performing client to the collaboration server. In order to avoid conflicts between the participants, the collaborative work is coordinated by means of locks. If an object is locked by a certain user it cannot be modified by any other user until the lock has been released.

The collaboration server provides an event service the clients can connect to in order to get notified about any modifications. For the purpose of clearly separating the different categories of information available, multiple event channels are used: The user event channel provides information on users entering and leaving the session, geometry modification events are transmitted via the geometry event channel, the concurrency control channel gives notification of locking and unlocking of objects and changes in semantic data are broadcasted by the semantics event channel.

Finally, we identified an easy-to-use audio connection as an essential component of a collaborative environment.

The clients serve as the visualization and interaction interface for the engineers taking part in the collaborative session. The following basic services should be provided by each client application:

- logging into / logging out of the collaboration server
- visualization of the geometric objects, interaction facilities for transforming them, support for locking mechanisms
- displaying semantic data attached to the geometric object (at least via attribute-value tables)
- displaying the current participants, notification of participants entering and leaving the session
- support for audio-conferencing

For the HVAC scenario in our example, we implemented a client, making it possible to transform the obstacles inside an office and visualize the CFD simulation data in the form of vector planes, iso-surfaces or streamlines. The client can be run in single-window mode capable of stereoscopic rendering (Figure 9) for use in Virtual-Reality environments, or in multi-window mode for use on desktop computers (Figure 7). Obstacles that are modified by another participant are given a different color and cannot be converted, i.e. they are locked.

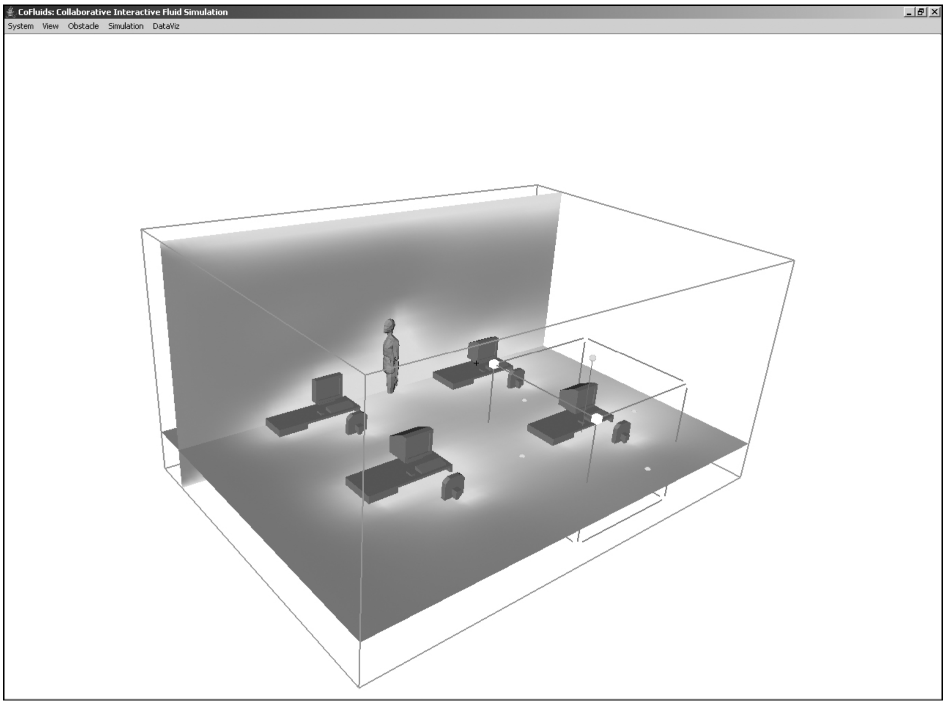


Figure 9. The collaborative client application for the HVAC engineer in single-window mode

The major task of a simulation server is to build a bridge between the distributed collaborative system and a particular simulation kernel. Like the clients, the simulation server is listening to the event channels provided by the collaboration server. It is accordingly notified of any changes in the geometry and the corresponding boundary conditions and can forward this information to the simulation kernel.

The minimum service that a simulation server should provide is an interface to start and stop the simulation and to pass steering parameters. It has to provide an event service, which notifies interested clients when the simulation begins and ends.
For computational steering applications it is very important that the communication overhead employed by the collaboration platform does not slow down the numerical computation. This can be achieved by using a separate machine as a simulation server.

5 CONCLUSIONS

This paper has presented concepts of error and model adaptive simulation in the context of a multi-disciplinary collaboration. In order to provide the collaborating engineers with suitable analysis and simulation capabilities, we have illustrated the flexible integration of product models and simulation servers into the distributed system. Whereas we concentrated our discussion on adaptivity to structural analysis using the p-version of FEM as simulation tool, the suitability of the collaboration platform has been proved by the implementation of clients and servers for a collaborative HVAC engineering scenario. It demonstrates the integration of a CFD simulation server whose kernel is based on the Lattice-Boltzmann method, thus providing an interactive fluid simulation.

REFERENCES

[1] B.A. Szabo and I. Babuska, Finite Element Analysis, John Wiley & Sons, (1991).

[2] Ch. Schwab, p- and hp-Finite Element Methods, Theory and Applications in Solid and Fluid Mechanics, Oxford University Press, (1998).

[3] A. Düster, H. Bröker and E. Rank, The p-version of the Finite Element Method for three-dimensional curved thin walled stuctures. International Journal of Numerical Methods in Engineering, (2001).

[4] E. Rank, H. Bröker, A. Düster, R. Krause and M. Rücker, The p-version of the finite element method for structural problems. In: Error-controlled Adaptive Finite Element Methods in Solid Mechanics, E. Stein (ed), John Wiley & Sons, (2001).

[5] A. Düster and E. Rank: A p-version finite element approach for two- and three-dimensional problems of the J2 flow theory with nonlinear isotropic hardening. International Journal of Numerical Methods in Engineering, (2002).

[6] B. Szabo, A. Düster and E. Rank, The p-version of the Finite Element Method. Chapter in: The Encyclopedia of Computational Mechanics, John Wiley an Sons, (2004).

[7] A.T. Noel and B.A. Szabo, Formulation of geometrically non-linear problems in the spatial reference frame. International Journal of Numerical Methods in Engineering, **40**:1263-1280, (1997).

[8] E. Stein and S. Ohnimus, Integrierte Lösungs- und Modelladaptivität für die Finite-Elemente-Methode von Flächentragwerken. Bauingenieur Bd. 73, Nr. 11, (1998).

[9] E. Rank, A. Düster and Z. Alam, Adaptive computation of thin-walled structures based on high order solid finite elements. In: Proceedings the WCCM VI in conjunction with APCOM ′04, Beijing, China (2004).

[10] R. Johansen, Groupware: Computer Support for Business Teams. The Free Press – Macmillan, New York, (1988).

[11] R. V. Liere, J. Mulder and J.V. Wijk, Computational Steering. Future Generation Computer Systems, Vol. **12**, N. 5, (1997).

[12] M. Krafczyk, Gitter-Boltzmann Methoden: Von der Theorie zur Anwendung, Professorial Dissertation, LS Bauinformatik, TU Munich, (2001).

[13] D. d'Humières, I. Ginzburg, M. Krafczyk, P. Lallemand and L.-S. Luo, Multiple-relaxation-time lattice Boltzmann models in three dimensions, Phil. Trans. R. Soc. Lond. A, **360**, pp. 437-451, (2002).

[14] P. Wenisch, C. van Treeck and E. Rank, Interactive Indoor Air Flow Analysis using High Performance Computing and Virtual Reality Techniques. In: Proc. of Roomvent. Coimbra, Portugal, (2004).

[15] B. Crouse, M. Krafczyk, S. Kühner, E. Rank and C. van Treeck, Indoor air flow analysis based on lattice Boltzmann methods, Int. J. Energy and Buildings, **34/9** pp. 941-949, Elsevier, (2002).

[16] A. Borrmann, P. Wenisch, C. van Treeck and E. Rank, Collaborative HVAC design using interactive fluid simulations: A geometry-focused collaboration platform, Proc. of CE05, (2005).