Collaborative HVAC design using interactive fluid simulations: A geometry-focused collaboration platform

A. Borrmann, P. Wenisch, C. van Treeck & E. Rank
Lehrstuhl für Bauinformatik, Technische Universität München, Germany

ABSTRACT: This paper presents a generic approach to realizing a collaboration platform integrating various simulation tools, thereby providing multi-disciplinary engineering teams with powerful analyzing facilities. In the proposed architecture, a common model is centrally managed by a collaboration server. This model basically consists of a geometric model enhanced by adding semantic data like boundary conditions for a certain simulation. Other important components of the architecture are dedicated simulation servers, which provide simulation and analysis data for the engineer's front-end application and can be connected to the platform on demand. The suitability of the concept is demonstrated by means of a concrete implementation for a collaborative engineering scenario in the Heating Ventilation Air Conditioning (HVAC) domain, incorporating an interactive fluid simulation.

1 INTRODUCTION

1.1 *Collaboration in planning processes*

The processes entailed in planning a building are characterized by a high degree of specialization and a fine division of labor. Moreover, there are numerous, complex inter-dependencies between the planning decisions. These aspects highlight the need for a close cooperation between the planners. Typically, the specialists from the numerous domains involved are not located at the same place or area, but distributed throughout the country or even the whole world.

According to Johansen (1988), 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. In our project we concentrate mainly on supporting synchronous collaboration phases. Nevertheless, most of the issues discussed in this paper apply to both the synchronous and the asynchronous collaboration mode.

Simulation and analysis tools play a major role in the engineering of buildings today, such as programs for structural analysis or computational fluid mechanics. This paper will introduce an approach for integrating these tools into a collaborative platform. They add a lot of relevance to a collaborative platform: during the collaborative session the specialist can use the simulation tool of his choice to obtain data necessary for his decisions. In contrast, the rather basic approaches for collaborative platforms we have seen up to now often lack this functionality, although we consider them to be vital in engineering practice.

1.2 *Collaborative HVAC engineering*

Exemplarily, this paper will tackle the demands of engineers working together to design the HVAC system of a building. In order to achieve optimal convenience for subsequent users, both the inlets and outlets of the air ventilation system and the radiators (heaters) have to be placed in the right positions. In addition, the air circulation inside a room or office also depends on the position of windows, doors and obstacles like plants or bookcases.

While the location and dimensions of the former are typically fixed at that stage of the design chain, the latter are still subject to discussion. The interior

Figure 1. HVAC engineers taking part in a collaborative session using different human-machine interfaces.

designer or an architect is usually involved in the decision-making.

A fairly characteristic scenario for planning processes involves specialists from different domains coming together to find an optimum solution for a given problem. To support this collaboration we provide them with a virtual space representing their common topic of interest. In the case of our example scenario, it is an office with its surrounding walls including their voids, the HVAC devices and the office equipment inside the room.

An important aspect of designing a collaborative platform is the fact that specialists from different domains make different demands on the application they are using while taking part in the collaborative session. Fairly simple approaches like desktop applications are often unsuitable. To analyze the indoor air flow, the HVAC engineer will use a CFD tool, while the interior designer might use a visualization software with advanced rendering capabilities in order to perform an illumination analysis.

1.3 *Computational Steering*

The classical method of conducting simulations and analysis for the design and engineering of buildings tends to be rather laborious: The geometry of the building - or parts of it - is taken from plans or building models and entered into the simulation or analysis tool. In most cases, this has to be done manually. After that, the geometric information is enhanced by adding more details representing boundary conditions for the simulation.

The simulation is implemented using the well-prepared input resulting from this ‘preprocessing’ stage. Depending on the computational effort of the simulation and the resources available, this can take up to several days, especially in the case of three-dimensional CFD-simulation.

When the simulation is finished, its results are visualized in order to make them easy for the engineer to interpret. This step is called ‘postprocessing’. If the engineer is not satisfied with the results, she has to reconfigure the simulation input, conduct the simulation and evaluate the results again. Since these three separate steps (pre-processing, simulation and post-processing) are frequently interrupted by manual data transfers between the different software tools, the optimization cycle usually takes a very long time.

In order to reduce the amount of time needed for simulation-based optimization cycles, we propose an integrated approach, called ‘computational steering’ (Liere et al., 1997). The idea is based on the increasing computational power available, making it possible to implement interactive simulations where the boundary conditions can be changed *while* the simulation is running. This enables the engineer to see how the simulation reacts to modifications and to optimize the boundary conditions intuitively.

The concept of computational steering will obtain even more relevancy when on-demand high performance computing becomes available, as proposed by the IntelliGrid project (Türk et al), for example. Also small and medium-sized companies will then benefit from the shorter optimization cycles.

Our team has developed a computational steering system for indoor computational fluid dynamics. The HVAC engineer can use it to position the radiators, the inlets and outlets of the air-conditioning system and the obstacles while simultaneously observing the effects on the air flow inside the room.

1.4 *Numerical method involved*

The numerical method involved is of high importance for the feasibility of computational steering. The CFD simulation kernel developed by the Lehrstuhl für Bauinformatik (Kühner 2003, Wenisch et al. 2004) for a computational steering prototype is based on the lattice-Boltzmann method.

During the past decade, lattice-Boltzmann methods (LBM) have emerged as a complementary technique for the computation of fluid flow phenomena (Krafzcyk 2001, van Treeck 2004). Common numerical methods for solving the Navier-Stokes equations are based on the discretization of the non-linear partial differential equations by applying finite volume or finite difference techniques, for instance. By contrast, LBM represent a bottom-up approach which starts at a discrete microscopic model preserving the desired quantities, such as mass and momentum, by construction in order to obtain hydrodynamic behavior on a macroscopic scale corresponding to the incompressible Navier-Stokes equations.

LBM perfectly meet the demands of computational steering, especially in terms of the possibilities for an interactive modification of geometric boundary conditions. It uses Cartesian grids, explicit time-stepping schemes and a marker-and-cell-like approach to define boundaries and obstacles.

Recently, LBM has been extended to include the simulation of turbulent convective flows. Although this has not yet been integrated into the simulation kernel used for the study in progress, the software will be upgraded very soon using a Bousinesq approach, as discussed in van Treeck (in press). For more detailed information on LB methods applied to indoor air flow simulations, see van Treeck (2004) and the references therein.

2 THE COMMON MODEL

In the approach presented here, the so-called ‘common model’ forms the basis of the collaboration system. This involved making a fundamental decision: should the core of the common model be a geometric or a semantic model? Should the geometric object (i.e. a solid) know its semantic meaning or should the semantic object know its geometric representation?

Most of the recently conducted scientific research in collaborative engineering and data exchange as well as the industry standard product model IFC follow the second approach: The core of the model is the semantics, the geometry is either generated from the objects' attributes or explicitly attached to it (Eastman 1999), (IAI 2004), (Romberg et al. 2004).

As opposed to other industries, such as electrical engineering, in building engineering geometry is one of the most important aspects of modeling the product on the computer. Geometry is where the design process starts: functionality, usability and aesthetics are defined by the shape of the product. For simulation tasks like structural analysis or computational fluid dynamics, it is the major source for defining boundary conditions.

While the variety of possible product models is endless, there is only a limited number of geometry representations used in practice: the constructive solid geometry (CSG) approach based on the concatenation of Boolean operations on simple shapes, and several boundary-representation (B-rep) models including those which represent the surface by means of plane facets and those which use parameterized patches (Mortenson 1985), (Mäntylä 1988).

Of course, a pure geometric model would not fulfill the demands of collaborative engineering. There will always be additional data to be shared among the participants. We have therefore decided to use a hybrid solution with the ability to attach semantic information to geometric objects in a generic way (Figure 2). This hybrid common model is centered by the geometric part: The geometry of an object is the information that all client applications can understand. The shape of an object is not implicitly stored in the attributes of the semantic model.

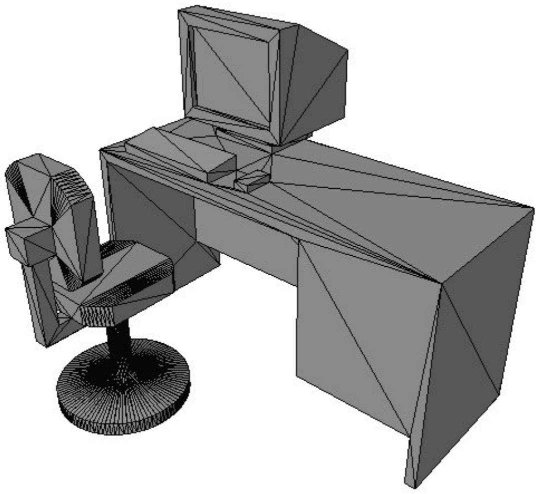


Figure 3. Office furniture represented as triangulated surface

A very similar approach is widely used in the automotive industry, where such a geometry-focused subset of the complete product model is called Digital-Mock Up (DMU). It is used for various simulation and analysis tasks during the development process, like crash-test calculations and mountability analysis (Döllner et al., 2000).

In the present phase of our project, the common model used by the collaboration server only supports a geometric representation based on a triangulated surface mesh (Figure 3). But we plan to enhance the capabilities of the model in order to support more complex geometric representations.

For attaching semantic data to a geometric object, a simple meta-model was integrated in the common model, as can be seen on the left hand side of Figure 2. It supports two aspects of the object-oriented modeling paradigm: encapsulation by providing classes as containers for attributes, and inheritance by making it possible to derive a class from a super-class.

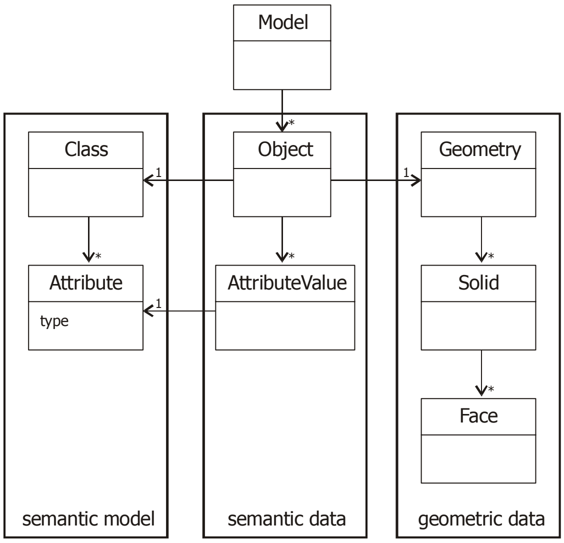


Figure 2. The hybrid common model

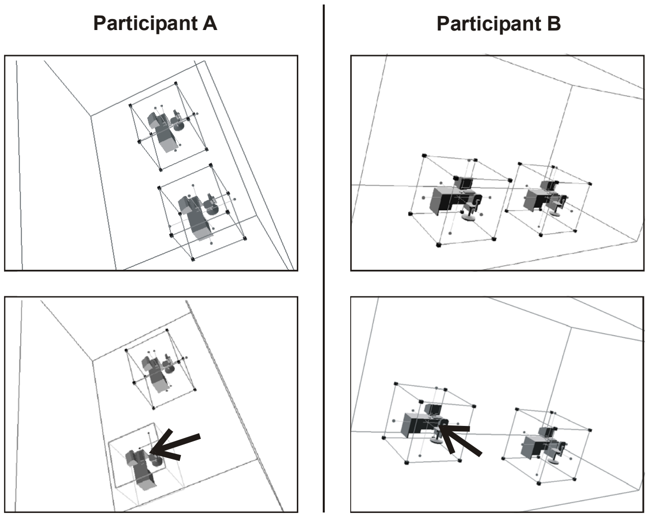


Figure 4. Independent views of two participants

The meta-model is not used to modify the semantic model during runtime. Instead, it has to be defined prior to the start of the collaborative session.

Using the meta-model makes customizing the collaboration platform easy, without the need to recompile the collaborative server. Unlike the collaborative server, which can handle semantic information in a generic way, both the client applications and the simulation servers have to know the precise identity of the semantic model used in their domain at compile time in order to process the semantic data accordingly.

3 THE ARCHITECTURE OF THE COLLABORATION PLATTFORM

3.1 *Overview*

The collaborative system 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 4). 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 5 shows these components and the communication paths between them. Each of the components can be run on different machines.

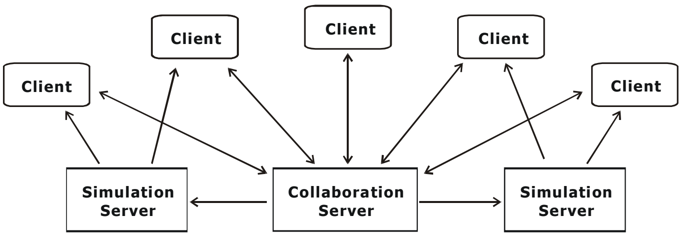


Figure 5. Overview of the multidisciplinary collaboration platform. Not every client has to receive simulation data and different clients can receive data from different simulation servers.

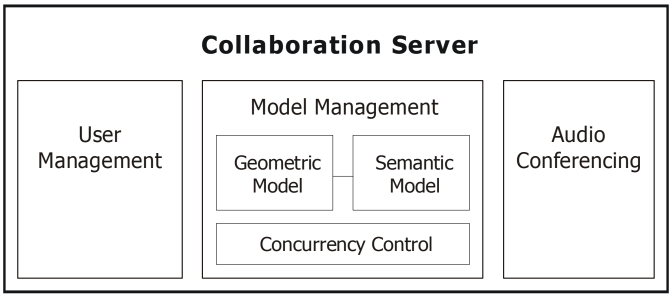


Figure 6. The modules of the collaboration server

3.2 *The Collaboration Server*

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

Each of these tasks corresponds with a dedicated module in the collaboration server as shown in Figure 6.

The core of the collaboration server is the model management module. As discussed in Section 2, 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 segregating 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.

3.3 *The clients*

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, isosurfaces or streamlines. The client can be run in single-window mode capable of stereoscopic rendering (Figure 7) for use in Virtual-Reality environments, or in multi-window mode for use on desktop computers (Figure 8). Obstacles that are modified by another participant are given a different color and cannot be converted, i.e. they are locked.

3.4 *The simulation server*

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.

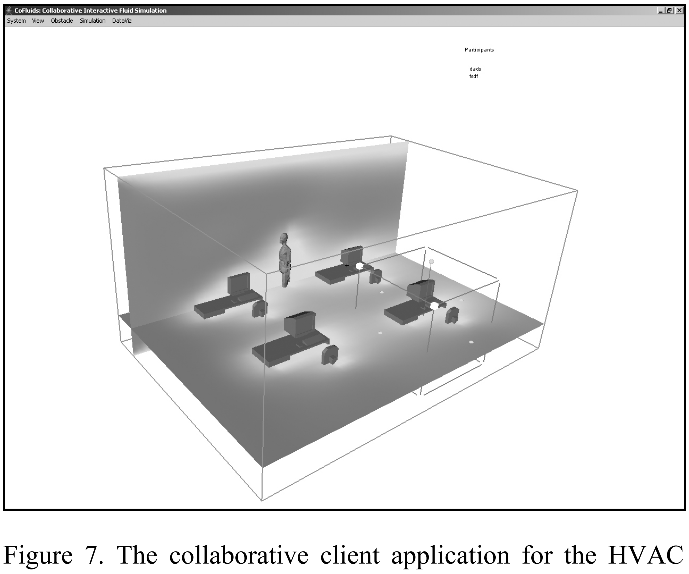
For computational steering applications it is very important that the communication overhead employed by the collaboration platform does not slow down the numerical computation. This can be achieved by using a separate machine as a simulation server.

4 CONCLUSION

This paper has presented the concept of a flexible multi-disciplinary collaboration platform. In order to provide the collaborating engineers with suitable analysis and simulation capabilities, we have illustrated the flexible integration of simulation servers into the distributed system. The suitability of the concept 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.

The basis of the collaboration platform is formed by a centrally managed hybrid model joining an explicit geometric and a variable semantic model. The focus lies on the geometric model, because of its vital importance for analysis and simulation tools and its domain-independent validity.

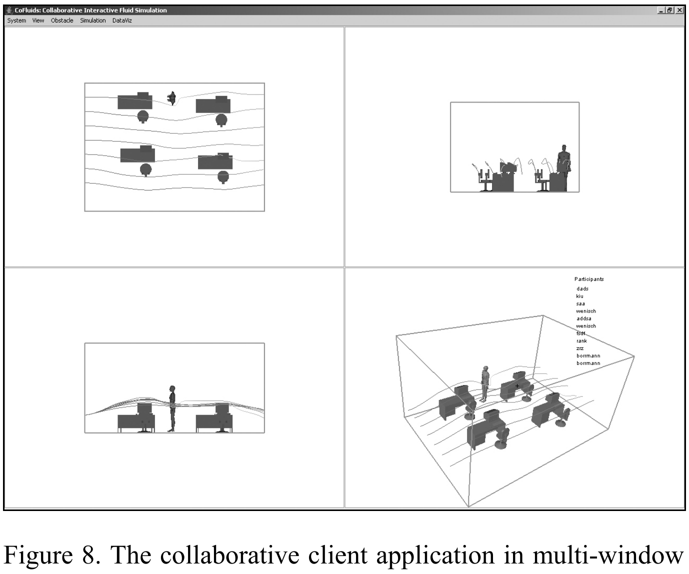
By separating the functionality of the collaboration server and the simulation server it is easy to integrate further applications into the collaborative system, which are able to participate in the collaborative session by receiving and sending information concerning the geometry, but receive different information or non-simulation data.



Participants

dads
fsdf

Figure 7. The collaborative client application for the HVAC engineer in single-window mode



Participants
dads
kiu
saa
wenisch
addsa
wenisch
fsdf
rank
zrz
borrmann
borrmann

Figure 8. The collaborative client application in multi-window mode

5 OUTLOOK

Our on-going research will continue to focus on supporting multi-disciplinary collaborative engineering. To this aim, a group concept is to be added to the user management. Besides the possibility of assigning modification rights to all members of a group, it will make it possible to provide group-specific semantic models.

Furthermore, we will tackle the management of a complete building model by means of the collaborative server. In order to minimize conflicts and mutual disturbance among engineers working simultaneously on a project, it is necessary to divide the building model into partial models, using spatial units such as floors or rooms.

Future work will also feature the integration of more sophisticated geometric models, such as CSG or parametric models, into the centrally managed model.

ACKNOWLEDGEMENT

We would like to thank Mr. Wenisch of the Leibniz Rechenzentrum (LRZ) in Munich for his support in developing the computational steering application.

The project presented here is supported by Siemens AG in Munich, Germany.

REFERENCES

Döllner, G., Kellner, P. & Tegel, O. 2000. *Digital Mock-Up and Rapid Prototyping in Automotive Product Development.* In: Journal of Integrated Design and Process Science, Vol. 4, No. 1, pp.55-66

Eastman, C. M. 1999. *Building Product Models: Computer Environments Supporting Design and Construction.* CRC Press, Boca Raton, Florida.

Johansen, R. 1988. *Groupware: Computer Support for Business Teams.* The Free Press – Macmillan, New York.

Kühner, S. 2003. *Virtual Reality basierte Analyse und interaktive Steuerung von Strömungssimulationen im Bauingenieurwesen.* PhD thesis, Technische Universität München, Germany.

Krafzcyk, M. 2001. *Gitter-Boltzmann-Methoden: Von der Theorie zur Anwendung*. Habilitation, Technische Universität München, Germany.

Liere, R. V., Mulder, J., Wijk, J. V. 1997. *Computational Steering*. Future Generation Computer Systems, Vol. 12, N. 5.

Mortenson, M. 1985. *Geometric Modeling*. Wiley, New York.

Mäntylä, M. 1988. *An Introduction to Solid Modeling.* Computer Science Press. College Park, MD.

Romberg, R., Niggl, A., van Treeck, C. & Rank, E. 2004. *Structural Analysis based on the Product Model Standard IFC.* In: Proc. of the 10th Intern. Conf. of Computing in Civil and Building Engineering (ICCCBE-X). Weimar, Germany.

van Treeck, C. & Rank, E. 2004. *Analysis of Building Structure and Topology Based on Graph Theory.* In: Proc. of the 10th Intern. Conf. of Computing in Civil and Building Engineering (ICCCBE-X). Weimar, Germany.

van Treeck, C. 2004. *Gebäudemodell-basierte Simulation von Raumluftströmungen*. PhD thesis, Technische Universität München, Germany.

van Treeck C., Rank, E., Krafczyk, M., Tölke, J. & Nachtwey, B. in press. *Extension of a hybrid thermal LBE scheme for Large-Eddy simulations of turbulent convective flows.* Computers and Fluids. Elsevier Science.

Turk. Z. et al. 2004. *Towards engineering on the grid.* In: Proc. of the 5th Europ. Conf. on Product and Process Modeling in the Building and Construction Industry (ECPPM). Istanbul, Turkey.

Wenisch, P.; van Treeck, C. & Rank, E. 2004. *Interactive Indoor Air Flow Analysis using High Performance Computing and Virtual Reality Techniques*. In: Proc. of Roomvent. Coimbra, Portugal.

IAI. 2004. *Industry Foundation Classes*. International Alliance for Interoperability. http://www.iai-international.org