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TOWARDS A MULTIMODEL APPROACH FOR SIMULATION OF CROWD BEHAVIOUR UNDER FIRE AND TOXIC GAS EXPANSION IN BUILDINGS

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ABSTRACT

A holistic approach for the simulation of evacuations from buildings in cases of fire and toxic gas spread is developed within the German project iSiGG to achieve high reliability in fire safety planning. Its essence is in the mutual interaction of the domains of crowd simulation, pollutant gas spread simulation (CFD) and Building Information Modeling (BIM), embedded in a coherent IT system. The conceptual basis of this system is provided by a dynamic multimodel ensuring interoperability of all system components and supplying simulation tasks with the necessary building and environmental data. More importantly, it allows to take into account various possible changes of the state of building elements, which may be caused by inhabitants or by the building control systems and can lead to strong changes in the simulation models. The simulations themselves are coupled on numerical level through a shared Voxel Model in a co-simulation approach.

1 OVERVIEW

This paper presents the concept and current development results of an interactive integrated simulation system for fire, smoke and pollutant gas spread in buildings in cases of fire, chemical, biological and radiological incidents and terrorist attacks developed in the German project iSiGG (07/2016-06/2019) in the frames of the IKT 2020 funding initiative. The developed approach will combine computational fluid dynamics (CFD) methods with methods for numerical simulation of people flow based on a semantic multimodel that is capable to support non-stationary changes of the model status such as opening/closing of doors and windows, state changes in the HVAC and the fire protection systems, damages due to blasts or people actions, etc.

The principal interactions that have to be supported by the system are shown on high level in Figure 1. The on-going development comprises the following tasks:

1. Development of a CFD simulation software specifically optimized for the targeted application domain of fire and toxic gas expansion in buildings;
2. Development of a crowd simulation tool with dedicated behaviour patterns for fire and hazardous context;
3. Coupling of CFD and people flow simulations to an integrated co-simulation using as baseline the Functional Mock-up approach (FMI 2014);
4. Enabling continuous interaction of the simulations with the building model data, considering also the possible dynamic state changes of the latter in the progress of the simulation process;
5. Embedding the simulation system into a BIM based virtual 3D Lab for building design;
6. Development of an application program interface (API) for modular integration of the simulation services in a compute cloud environment for achievement of fast online response.

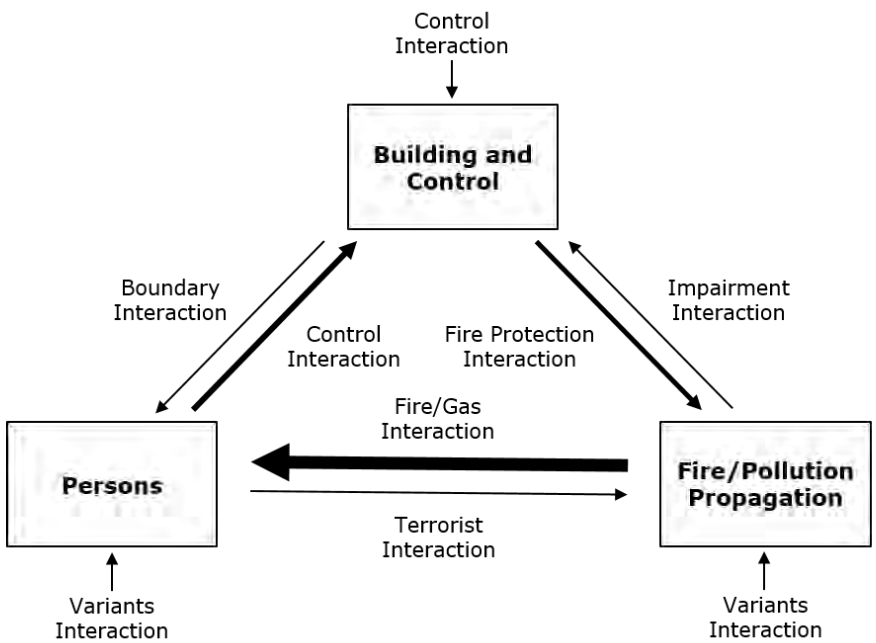

Figure 1: Systems interaction.

The CFD system is based on an existing software application for the simulation of fire in tunnels (Kanellos et al. 2016). It will be strongly extended by an open library of building materials including functions for material heat release rates, consideration of HVAC equipment, coupling of the mass transport and the Navier-Stokes equations, and combination of fire and smoke spread models with a radiological model.

The people flow simulation will be based on the multi-purpose agent simulation system AnyLogic (AnyLogic 2013), extended by a database for human behaviour patterns combining physical and psychological models and considering CFD and building element interactions.

Building modelling is based on the standard IFC model (ISO 16739) and the multimodel method originally developed in the German project Mefisto (Schapke et al. 2014) and the European project HESMOS (Liebich et al. 2013). Details of the method are presented in project reports available via the web sites of the mentioned projects (www.mefisto-bau.de, www.hesmos.eu). The method is currently extended in the new ISO endeavour Information Container for Data Drop, ICDD (ISO/NP 21597). It will enable (1) dynamic modelling of building elements and technical equipment, (2) dynamic linking of the three modelling subdomains (building, CFD, people flow), and (3) use of rule-based methods for automated derivation of model change states.

The developed simulation system will be of benefit for a number of different actors in the construction process such as designers, facility managers, owners, security personnel, public authorities and insurances, especially with regard to the planning of safety measures, the evaluation of existing buildings and the development of training scenarios for rescue and security teams. The integrated multimodel BIM functionality will enable easy to use visual examination of evacuation plans and virtual team training thereby helping to improve the overall quality of the design process regarding high-rise buildings, shopping malls, railway stations and airport terminals.

2 BACKGROUND

Today, the demand for higher building security has grown considerably, especially for evacuations in cases of fire, chemical, biological and radiological incidents or terrorist attacks. However, the planning of relevant safety measures for new buildings or the evaluation of existing buildings requires reliable information for a farsighted decision making. Simulation tools that can realistically map the spread of fire, smoke and pollutants in buildings already exist, but they are conventionally based on 1D or single zone static models which allows only rough estimation of the safety. As a result, decision making is typically very conservative and does not consider the consequences of possible intervening measures. Accordingly, safety and rescue operation plans are subject to a high degree of uncertainty with regard to their effects. Therefore, more and more often realistic 3D CFD simulations are being asked for, which is becoming possible with the continuous growth of computer power. However, such simulations are still very costly and time-consuming, especially with regard to the involved modelling efforts.

In recent years, approaches that combine CFD simulation with evacuation planning have also been investigated (Tang and Ren 2008; Shi et al. 2009) but they are still too approximate and as yet insufficiently precise for reliable safety investigations of buildings. Furthermore, there is a lack of interoperability to BIM which leads to cumbersome and error-prone information preparation and limits considerably simulation tool interaction and the overall process automation. The approach presented in the following sections is a step towards the solution of such shortcomings.

3 INFORMATION SYSTEM

The proposed evacuation simulation system connects 3 different modelling domains, namely: (1) people movement, (2) fire and toxic gas expansion, and (3) the building with some non-static and non-stationary elements including technical building systems like sprinkler, HVAC, automation control and security systems.

The building model defines the spaces and the related boundaries for the movement of people and the fire and toxic gas expansion. However, the building is not a stationary, unchangeable object but contains various elements that may change their state and affect the physical simulation models. Such elements are the doors and windows which can be locked, closed, open or broken, as well as various other building components that can burn due to fire, burst due to people's actions or blast due to pressure and hence be destroyed partially or completely causing changes in the spaces and the related spatial boundaries. In addition, actions and reactions of the technical building systems that may cause changes of physical boundary conditions must also be taken into account as e.g. automatic or forced sprinkler activation, sucking/blowing of air by the AC system etc. Many of these are events that cannot be strictly predicted but their occurrence has to be considered by the two simulation domains (see Figure 1).

The gas expansion and the evacuation of the inhabitants is a co-simulation of the two domains regarding the movement of people and the fire, smoke or toxic gas spread in the building subject to various environmental factors. However, for each domain a different spatiotemporal model is applied. The CFD gas spread simulation is more detailed by orders of magnitude than the simulation of people flow, both in terms of space zones and time. Hence, synchronization of the two simulation domains, i.e. the achievement of their physical interoperability, is done in discrete-continuous manner, on the level of the people flow model with one interaction point per person, and not at each time step of the CFD simulation and the exact surface of interaction of each person with the environment.

To achieve that physical interoperability we suggest an approximation by *voxelization*, with 3 voxels in height for each modeled adult person. Thus, the common interaction medium is a voxel discretization with a stationary voxel mesh. Consequently, the fine-grained discretization of the CFD domain is mapped at each synchronization step to a single parameter set per voxel. People are thereby discretized to be always completely enclosed by 3 static voxels. In this discrete-continuous synchronization of the two simulation domains the modelling of the building data plays only a subordinate role, mainly as static provider of the initial bulk of data for the simulation environment. However, the described discrete-continuous physical interoperability of the two simulation domains has to be superimposed by the possible event-driven changes in the system that must be investigated as well to provide for reliable decision making. Thus, the interaction problem between the 3 domains is sub-structured in 2 interaction problems, a *discrete-continuous* high frequency interaction and an *event-driven* low frequency interaction, whereby the latter defines a new system state for the discrete-continuous interaction.

Accordingly, a 2-level modelling approach is suggested. For the event-driven interaction a multimodel approach based on the semantic interoperability of the 3 main domain models (building, people and gas flow) is applied to propagate properly all dynamic changes in the system caused by the interactions of the 3 domains. In contrast, for the discrete-continuous interaction of the simulation domains a pure numerical data synchronization is targeted to reduce the computational complexity. It is modelled by co-simulation interfaces and must be very fast to provide for near real-time response. Hence, the data to be exchanged have to be very lean. Only vectors of predefined data types are exchanged where each voxel state is defined by one such vector.

The foundation of the overall information system is provided by the BIM model in IFC which is a digital building representation describing the logical configuration of the building structures (walls, slabs, doors, windows, etc.) along with their properties, interrelationships and 3D geometry. Correct parsing of a relevant subset of the BIM model by both the CFD and the crowd flow simulation is thereby mandatory to ensure their cross-model semantic interoperability. However, the BIM/IFC model alone is not sufficient as it does not cover the full information needs of the two simulations. Additionally, data about the behavior and the location of the inhabitants are needed to start a crowd flow simulation, and the CFD simulation requires data for the location of the fire or the pollutant gas source as well as related fire, infiltration or pressure resistance properties of the materials used in the building. Fortunately, the data from these different domains can be united using the multimodel approach described by Fuchs and Scherer (2017), which enables connecting the domain models to a *multimodel* to solve cross-domain tasks. Thus, a shared data environment is created which allows filtering, querying and reasoning across the models. The relations between the models are established and formalized in separate Link Models where all inter-model links are defined using unique attributes of the related model elements as keys. Beside the advantage of a shared data environment, this approach also does not require the change of existing models, which is especially important for standardized data models like the IFC.

For the combined simulation of crowd flow and CFD fire or gas spread simulation a multimodel is used to describe the scenario. Beside the building model, which provides the geometrical frame of the simulation, the following models are included in the multimodel:

- *Inhabitants Model*, specifying behavior and location of the inhabitants on topological level which allows to create crowd flow scenarios independent of a specific building geometry;
- *Material Model*, specifying a material library which contains specific properties of the building materials related to the simulations;
- *Ignition Model*, specifying data about the ignition behavior for the fire scenario.

These 3 models are all linked to the building model to annotate the required BIM data whereby the topological elements of the inhabitants model (rooms, entrances, exits etc.), the materials from the material model and the ignition points from the ignition model are linked to the corresponding building elements in the building model. Thus, a complete scenario can be described and digitally processed, whereas the singular models remain independent from the considered building, increasing the reusability of the models to create other (variant) simulation scenarios.

However, although the multimodel approach enables consistent cross-domain interoperability and coherent model preparation for the simulations, manual linking of the model elements requires user knowledge about all three domains which is very challenging and also very time and cost consuming. To tackle this problem, we aim to support semi-automatic link creation by applying an *ontology framework* inspired by previous work in the European eeEmbedded project (Kadolsky et al. 2014). Ontologies allow the formalization of knowledge and facilitate knowledge processing in software components. Accordingly, link creation for the multimodel will be implemented using reasoning mechanisms and ontology-based rules describing various dependencies within and between the models in the multimodel. This approach can be also used to check the quality of the simulation results. Even more importantly, ontology use can provide for more detailed and efficient representation of the required model dynamicity. Besides the change of the state of certain model elements (such as the locking, closing. Opening or bursting of windows and doors) which can be achieved by respective model annotations, ontology rules can help to recognize and apply more complex interrelationships such as the locking or unlocking of doors or windows caused by a certain action of the building automation control or the building security systems, or cascading on/off switching of devices caused by exceeding a certain temperature, humidity or gas saturation threshold. Such cases may cause significant changes in the simulation process which would otherwise remain unrecognized.

4 SIMULATION SYSTEM

As already mentioned, the simulation system comprises the CFD pollutant gas spread simulation tool, the crowd flow simulation tool and the voxel based link interface providing for their physical interoperability.

4.1 CFD Pollutant Gas Spread Simulation

The developed CFD simulation tool is a parallel, multi-threaded application for the simulation of fire events inside and/or outside of buildings in the urban environment. It can be used for the simulation of 3D, unsteady, turbulent, incompressible flows enhanced with energy equations for the simulation of heat transfer effects. CFD simulations provide detailed temporal and spatial distribution of flow field variables such as temperature, velocities, contaminants concentration, smoke and other volatile components concentration. The distribution of these quantities are the critical parameters for the determination of people flow simulation and the assessment of injuries during the evolution of a fire event in buildings. The main characteristics of the implemented numerical method are as follows:

- Flow and heat transfer equations are solved strongly coupled;
- Buoyancy terms are incorporated in flow equations and in the turbulence models (k-ε with wall functions, low-Re k-ω SST, k-ω SST with wall functions, LES);
- Two radiation models (analytical and finite volume methods) are used for the simulation of radiative heat transfer.

The method is based on the pseudocompressibility concept for the solution of steady/unsteady, 2D/3D, turbulent flows and the use of hybrid meshes. It features a dual time stepping algorithm, a second order three point backward scheme in physical time, and a first order backward Euler implicit scheme in pseudotime. Local time stepping in pseudotime is applied for convergence acceleration. An upwind scheme for inviscid fluxes is used (second or third order accurate for mean flow and first order accurate for turbulence model), and a central scheme for viscous fluxes (second order accurate). Navier-Stokes equations are integrated in hybrid meshes that consist of hexahedra, pyramids, prisms and tetrahedral elements. A typical mesh size for the discretization of multiple zones in a building (e.g. 8 zones, 200 sqm) may thereby comprise over 10 million elements/nodes.

To be applicable for interactive use and physical training purposes, a simplified yet accurate enough CFD approach has been developed. The new algorithm is based on the Fast Fluid Dynamics technique, FFD (Jin et al. 2012) and parallelized for use on GPUs. It uses many parts of the original CFD code as they are, and especially the unstructured numerical mesh, to be able to exchange data between the two simulations and to ease the calibration procedure of the FFD simulations according to the CFD ones. The simplifications applied for the FFD approach are summarized as follows:

- Simplified models for the simulation of turbulence
- First order upwind schemes for the inviscid fluxes
- Thin shear layer approximation for the viscous fluxes whereby the surface unit normal vector “n” is approximately equal to edge direction vector “r_{ij}”
- First order time integration scheme (Euler implicit)
- Numerical meshes comprised of tetrahedral elements only (hybrid grids are split)
- Picard linearization for the velocity prediction step (surface normal velocity taken from previous Picard iteration step)
- Temperature-Concentration equations solved separately from other equations.

For the purposes of fire and plume dispersion incidents, both CFD and FFD codes are enhanced with fire suppression systems, namely sprinklers and HVAC systems. Sprinklers’ numerical simulation is based on Lagrangean techniques that follow the trajectory of each particular droplet of the water mist that is injected by the sprinkler jet. The simulation includes models for sprinkler activation, atomization, spray dispersion and surface cooling (by drops). The behaviour of sprinkler sprays is strongly coupled with the fire dynamics in the surrounding environment, by adding heat transfer terms in the heat transport equation representing the heat exchange between mean flow and droplets and resistant forces acting on the droplets into the momentum Navier-Stokes equations.

4.2 Crowd Flow Simulation

Behavior of people during evacuation in case of emergency is modeled using the agent based simulation tool Anylogic (cf. Anylogic 2013). A Social Force Model is used in Anylogic in order to determine the movement of people. In the Social Force Model three different forces affect the inhabitants and thus influence their direction of motion: the *desire force*, the *repulsive force* between persons and the *repulsive force* between a person and obstacles (e.g. walls).

The simulation model is created using the Pedestrian Library in Anylogic. This library contains logic elements defining the behavior of people. It has been extended by a number of behavioral patterns for the targeted fire and toxic gas spread scenarios and is made available using a process data base. Thus, even though for each specific building a different behavior will be observed, it will follow designated patterns taken from the process data base.

In addition to the processes defining behavior, markup elements are used to define the structure of the environment where people are moving in. These markups are also stored as part of the data base and are used for modelling entrances, exits, obstacles and service parts. In a stand-alone simulation they have to be defined manually based on a given layout of the building which is a very time-consuming and error-prone process. However, by using the interface to BIM enabled by the underlying multimodel information system, the markup elements can be created almost fully automatically.

The library IFC Java Toolbox (www.apstex.com) is used to load all elements of the building model in the crowd flow simulation tool. This library maps IFC elements to Java classes. Walls, windows, and doors are thereby different IFC elements. The correct position of windows and doors in walls is used to generate markup elements with openings where people can pass.

Fire and smog have an impact on the movement of people in case of emergency. The *Social Force Model* is adopted in Anylogic for considering such patterns of (changed) behavior in a crowd based on findings of Bae and Ryou (2015). The approach differentiates between people which are outside the smoke area and those which are inside it.

Helbing et al. (2002) describe that the Social Force Model also changes in case of panic situations. However, influences from panic are not part of current considerations.

4.3 Linking the CFD and the Crowd Flow Simulation

The two platforms CFD and crowd flow simulation are interlinked in order to exchange and synchronize data during a co-simulation run. CFD provides temperature, smoke concentration and visibility in given time steps. These values have an impact on the behavior of people in the building model during evacuation. Additionally, state of windows and doors can change when people open or close these elements. This state influences the extension of fire and smoke in a building. Crowd flow simulation must send information of such state changes to CFD simulation.

Data of fire and smoke are provided by the CFD simulation using a voxel model. The building model is divided into a grid of voxels with a constant length, whereby CFD and crowd flow simulation use the same voxel grid. Figure 2 shows an example of a voxel grid for the simulation model of a night club based on data from Grosshandler et al. (2005).

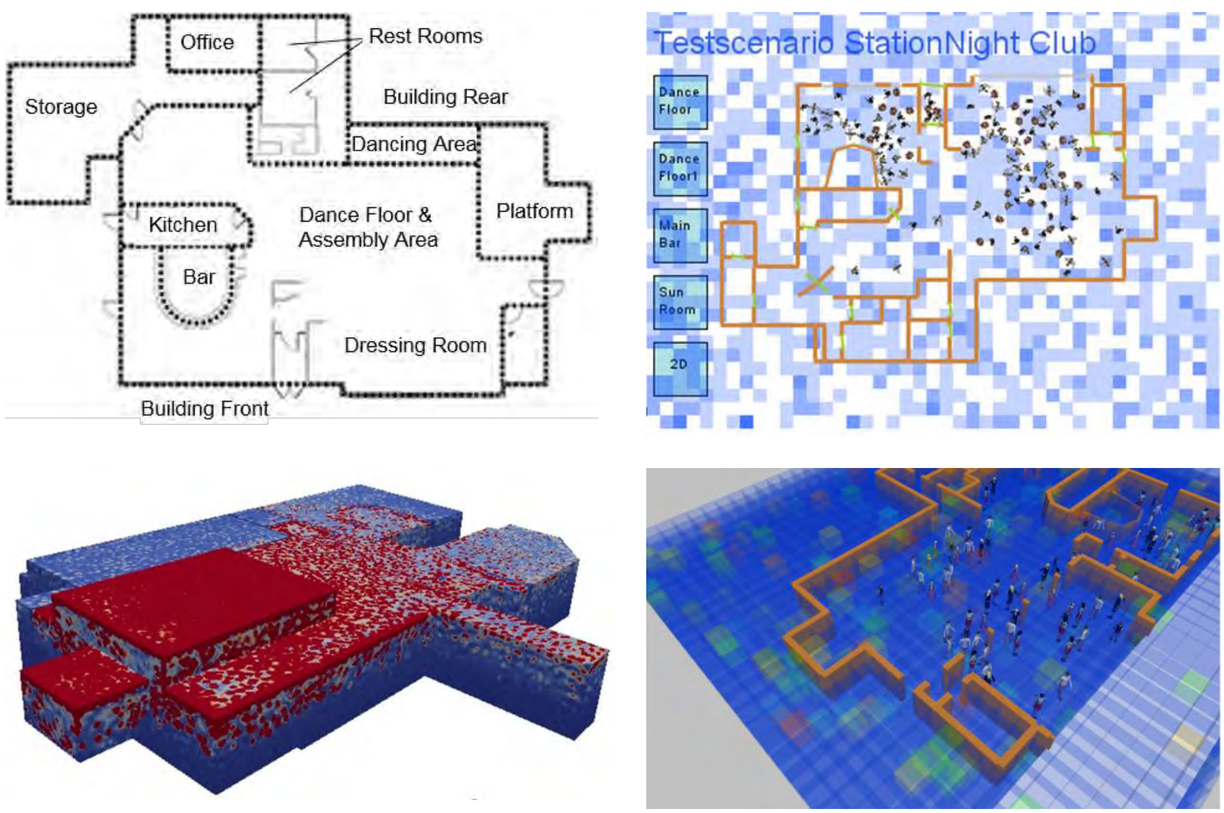

Figure 2: Interlinking of the simulation models for the studied night club incident - Night Club Room model (top left); Voxel model with animation of parameter values (top right); Concentration of contaminants (CO) in the CFD simulation (bot. left); and People flow in the Anylogic simulation (bot. right).

One of the main issues of calculating forces which are caused by smoke is the identification of fire and smoke clouds based on the voxel information. Direction and intensity of the repulsive force is determined based on the vector to the border of the smoke cloud with the minimum length. A voxel is at the outer limit of a cloud if the neighboring voxel has such a low concentration that the smoke or gas cannot be sensed.

5 CURRENT RESULTS

At the current stage, the CFD gas spread and crowd flow co-simulation as well as the static multimodel interface BIM-CFD-Crowd Flow based on the standard IFC building model are almost fully developed whereas the development of the dynamic BIM modelling components and the respective interfaces with the co-simulation system are work in progress expected to be presented by the end of the year.

Figure 3 shows the architecture of the system applied to realize the interaction between CFD and crowd flow simulation on the physical interoperability level. A Scenario Manager embedded in the SimController Component is used to define the parameter settings of the examined simulation scenarios. These settings include the initial state of the building (i.e. number and locations of people, state of elements like doors and windows), and start time and location of the fire or toxic gas source. All such settings are saved in a Multi Model Container following the ICDD approach (ISO/NP 21597), which is used in the data exchanges between the two simulation domains.

The communication scenario is established by the developed extendable software package SimAssist. The start parameters of the two simulation platforms and the used ports are predefined. The communication between CFD and crowd flow simulation is realized using a communication layer provided by the developed SimController, which is responsible for establishing the connection between the two simulation systems, starting a simulation run, message routing and transfer of status information to synchronize the co-simulation. A TCP/IP interface is used to exchange the element states and the voxel data.

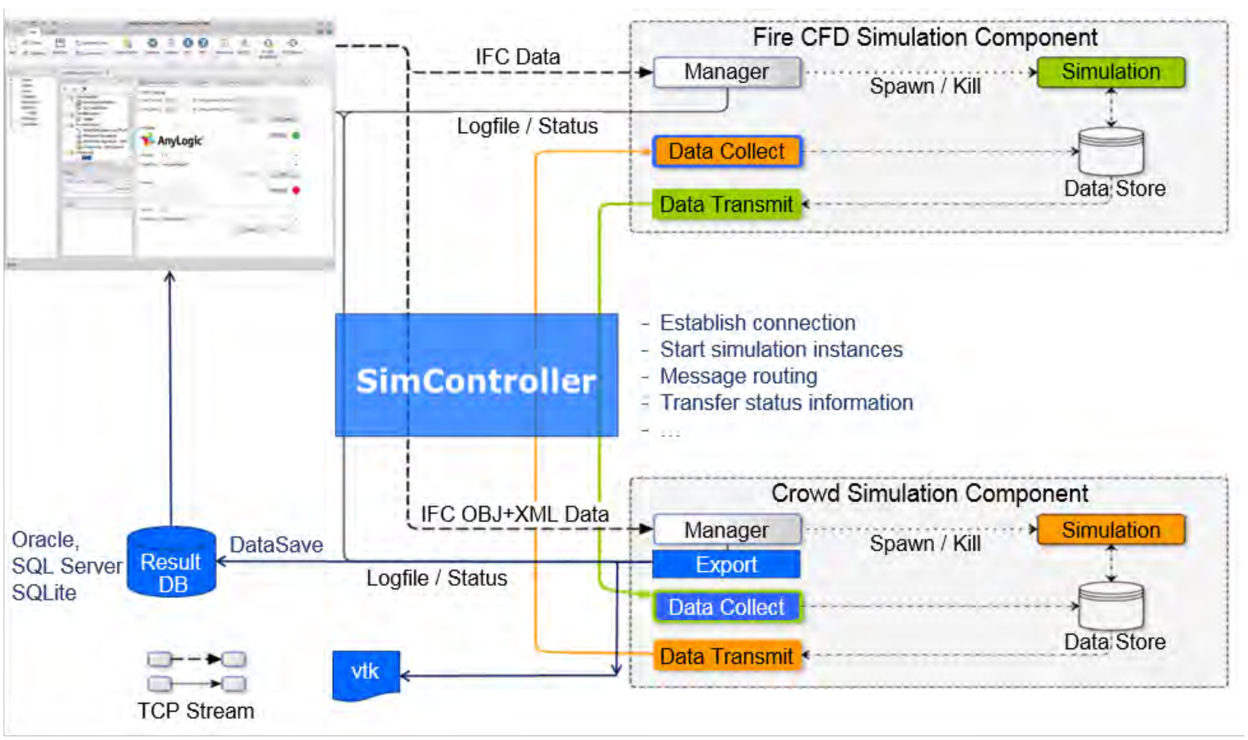

Figure 3: System Architecture of Data Exchange between CFD and Crowd Flow Simulation.

To achieve interoperability, both Simulation Components are structured in similar manner, complementing the actual simulation kernels with four additional modules, namely (1) Manager, responsible for simulation scenario synchronization, (2) Data Collect, responsible for receiving and processing the data transmitted by the other co-simulation, (3) Data Transmit, responsible for sending all state changes whenever necessary, and (4) Simulation Update, responsible for the internal status update of the numerical simulation model used. In addition, the Crowd Simulation Component features an Export module, which is used to store the final results persistently in a SQL database.

The principal communication scenario is shown in Figure 4. SimAssist initially starts the crowd flow simulation and sends a starting message. The CFD simulation is then triggered directly by the crowd flow simulation model. The crowd flow simulation model confirms the successful start of the complete scenario when CFD has responded.

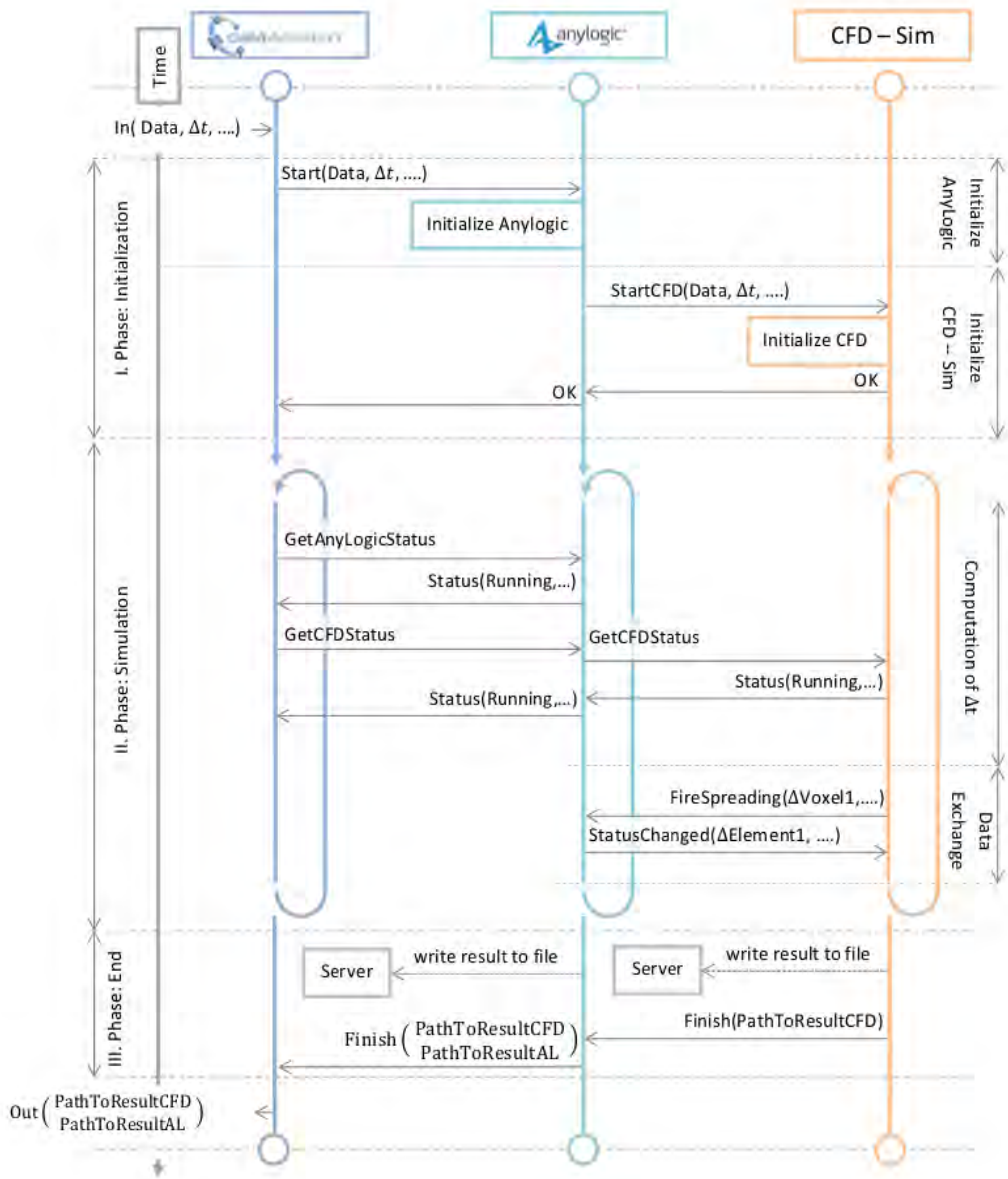

Figure 4: Principal scenario of a Co-Simulation Run.

There are different communication cases between SimAssist, the crowd flow simulation and the CFD simulation possible. SimAssist frequently requests the state of the simulation run by the crowd flow simulation and the crowd flow simulation requests this by the CFD simulation. Data are sent via so called "telegrams". The data exchange takes place in given time steps from the CFD to the crowd flow simulation. Data of voxels are sent only when a value change is recognized which reduces drastically the amount of exchanged data. In the opposite direction, the crowd flow simulation sends information of state changes of building elements (e.g. doors or windows) to the CFD. The telegram includes the IFC IDs of the related building elements and their new states.

Results of the crowd flow and the CFD simulation are saved frequently and at the end of the simulation run to the data base. The CFD simulation sends a final message including the path of the result data to the crowd flow simulation when all calculations are completed. The crowd flow simulation communicates the end of the simulation run and the location of the results of both tools to SimAssist. SimAssist can finally be used to analyze and visualize all results of the simulation run.

6 CONCLUSIONS AND FURTHER WORK

Simple simulation models focus in most cases on one domain from the real world. However, representing meaningful simulation results needs to consider different domains modeled by different methods. To tackle that challenge, in the preceding chapters of this paper we presented the concept and the achieved first results of an IT environment for co-simulation of fire and toxic gas expansion in buildings and the people flow interacting with it, taking into account their interface with the digital building information model and the possible dynamic changes of that model in the course of the fire or toxic gas spread incident.

The co-simulation is grounded on a suggested new multimodel information system that provides interoperability on two levels, the *physical interoperability* between the simulation tools which uses a voxel model as basis, and the *semantic interoperability* of the underlying modelling domains which uses the standard BIM/IFC model as basis. The first supports the efficient discrete-continuous synchronization of the two simulation domains by exchanging the minimum information necessary to inform each simulation about relevant changes caused by the other. The second supports event-driven cross-domain interrelationships that have to be appropriately mapped to the simulation models whenever happening, thereby enabling highly automated definition and execution of different "what-if" scenarios. This separation of the two interoperability levels leads to a lean, computationally more efficient and better performing system than any one-level integration approach and any stand-alone solutions.

The achieved promising first results give confidence with regard to the validity and applicability of the concept in practice. The on-going work regarding the consideration of dynamic state changes in the models, especially after inclusion of HVAC, building automation control and security systems, is expected to lead to better grounded and more reliable decision making than currently practiced. Moreover, the planned development of a Variation Model, which will enable fully automatic generation of various event-related scenarios and their parallel investigation with the help of cloud computing and modern result visualization technologies, is expected to contribute considerably towards increasing the quality of both safety planning and emergency training. The results of this work will be presented in reports and publications of the on-going iSiGG project (07/2016-06/2019), together with details on the applied voxelation technique, the ontology-based method for the multimodel approach, the interface to the BIM and the coupled numerical simulation outputs, which could not be shown here due to the given page limitations.

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