Multi-resolution Models: Recent Progress in Coupling 3D Geometry to Environmental Numerical Simulation

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Abstract In this paper, we present recent results on coupling geographic, infrastructure, and building models to multi-resolution numerical simulations. In order to achieve this, a parallel data access framework with interfaces to all parts of the simulation pipeline such as pre-processing, numerical simulation, and post-processing has been developed. The applicability of the approach presented in this work is shown by simulating urban flooding including surface flow of a city, the pipe network interaction, and its consequences to individual buildings. While the real life city model including the drainage system has been provided by the authorities of the city of Munich and comprises an area of about 2 by 2 km with detailed topography and a complete set of approximately 3,000 buildings modelled on LOD 1 of CityGML, IFC-models are the initial starting points for generating octrees on the level of individual buildings. In order to investigate the effects of the drainage system collapsing due to a heavy rain scenario, a fully three-dimensional parallel free surface flow simulation is incorporated with the interaction of the one-dimensional pipe-network flow. The whole simulation is performed on three levels of resolution, each of which is discretised by a fast voxelisation algorithm to generate a computational grid for the CFD simulation.

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1 Introduction

Many important scientific and technological developments in the last few decades have resulted in a tremendous increase in availability of 3D geometric models on different scales. To name a few, Google Earth is a many-scale model with resolutions from continental down to building scale, 3D Geographic Information Systems (GIS) (Yeung and Lo 2002; Bolstad 2005) such as CityGML (Kolbe et al. 2005; Kolbe 2007) are available for entire cities and regions, Building Information Models (BIM)[1] (SCRA 2006; Pazlar and Turk 2008) are starting to revolutionise planning and construction of buildings and infrastructure. All these models can be made available via the internet always and everywhere. Yet, whereas GIS and BIM are very well established as complex information resources and widely used for various planning aspects, they are much less established as a basis for advanced numerical simulations. On the other hand, tremendous progress has been observed in computational sciences and engineering over the past decades, making it now possible to perform large scale computations based on geometric models spanning many spatial and also temporal scales. Earthquake simulation is one area with spectacular advances in recent years, and material scientists start to understand structural behaviour by micro-macroscopic simulation based on first geometric and physical principles. In this paper, we will present recent results on coupling geographic, infrastructure, and building models to multi-resolution numerical simulations. In order to achieve this, a parallel data access framework with interfaces to all parts of the simulation pipeline such as pre-processing, numerical simulation, and post-processing has been developed.

Our discussion will first focus on suitable distributed data structures to store these models, building on forests of space-tree models. On a global level, an octree is defined, yielding efficient access to all objects in a city model. Leafs of this octree contain pointers to at most one building or infrastructure object. These local objects with all their components and construction elements are stored themselves using space-trees with access not only to geometric but also to semantic information via the underlying building information model.

From this hierarchical data model the framework now allows to derive all necessary input for a multi-resolution numerical simulation. We will concentrate in this paper on computational fluid dynamics (CFD), noting that other types of simulation such as traffic flow or evacuation scenarios could be addressed by the same conceptual approach. Starting from the large-scale model, a grid of voxels is derived. For realistic simulations these grids tend to be huge, and demand for specialised algorithms which take advantage of high-performance computing. Simulation results from this global model are now projected to initial and boundary conditions for simulations on local computational models which are, depending on the desired resolution, derived from the suitable levels of the multi-resolution geometric models.

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[1] BuildingSMART. http://www.buildingsmart-tech.org/speci.cations/ifc-releases/ifc4-release.

The applicability of the complete approach presented in this work is shown by simulating urban flooding including surface flow of a city, the pipe network interaction, and its consequences to individual buildings. While the real life city model including the drainage system has been provided by the authorities of the City of Munich and comprises an area of about 2 by 2 km with detailed topography and a complete set of approximately 3,000 buildings modelled on LOD 1 of CityGML, IFC-models are the initial starting points for generating octrees on the level of individual buildings. In order to investigate the effects of the drainage system collapsing due to a heavy rain scenario, a fully three-dimensional parallel free surface flow simulation is incorporated with the interaction of the one-dimensional pipe-network flow. The whole simulation is performed on three levels of resolution, each of which is discretised by a fast voxelisation algorithm to generate a computational grid for the CFD simulation.

2 Framework

One contribution of this work focuses on the development of a framework for handling large amounts of complex data, providing efficient access and evaluation strategies to retrieve and process these data in real-time, including fully detailed product model data of constructions and built infrastructure, large scale GIS data such as highly resolved terrain descriptions, and the definition of pipe networks. Furthermore, a city model definition is given which embeds individual buildings in the urban context, see Figs. 1 and 2 for examples representing different scales.

In order to efficiently organise and orchestrate those different data in one integrating structure, a hierarchical approach is used. Therefore, a so-called *first level octree* is generated based solely on the bounding boxes of all product models.

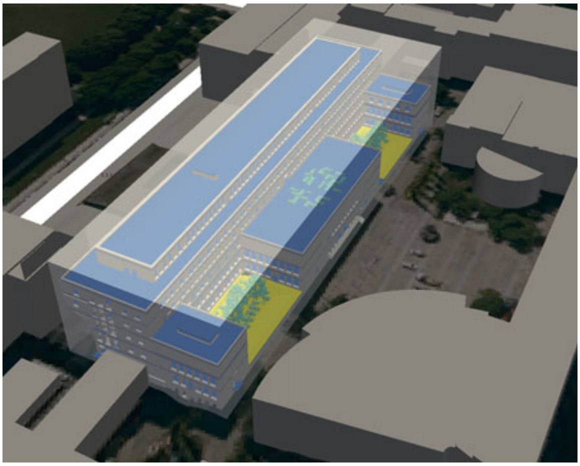

Fig. 1 City model (showing Technische Universität München's main campus) consisting of terrain, GIS, and highly detailed BIM data

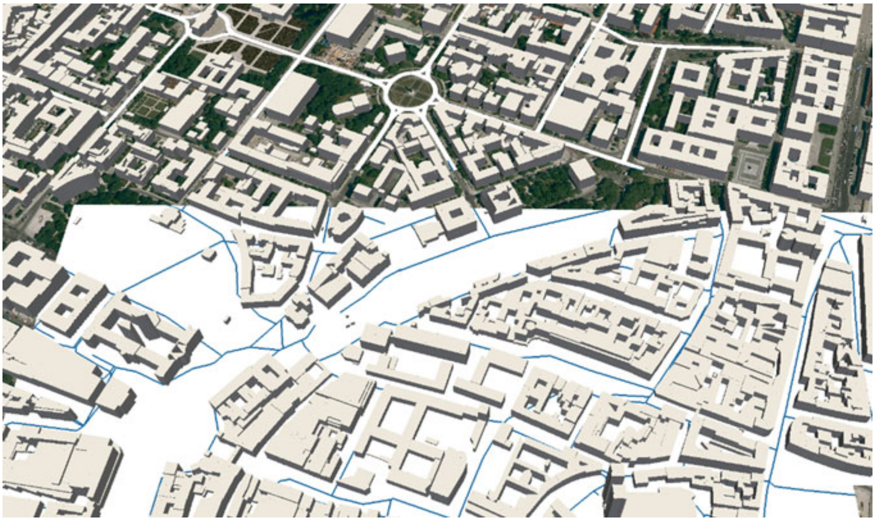

Fig. 2 City model (showing Munich City Centre) consisting of terrain and GIS data including the underground water drainage system

Instead of storing the model data itself, the voxels contain just a link to the corresponding resource, i.e. the location of the respective file containing the real product model data, see Fig. 3.

As this first level octree contains only links to product models instead of real data, a nearly unlimited number of constructions and buildings can be efficiently orchestrated by this approach even in real-time. Any access to specific product model data is possible at all times, while questions concerning range or proximity of buildings can be answered directly from the first level octree. Nevertheless, to process several product model data in real-time, a parallel concept has been developed. A master process assigns different product model data to its slave

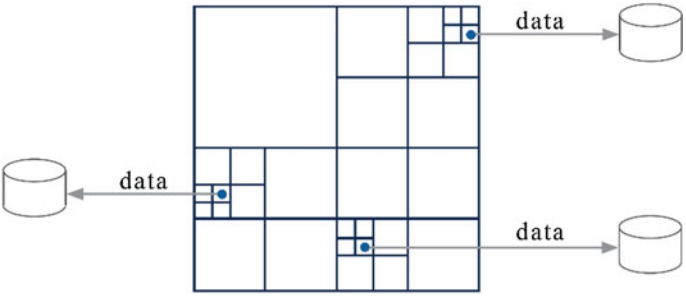

Fig. 3 First level octree of an entire region or city storing/providing links to the corresponding product model (IFC) or CityGML data

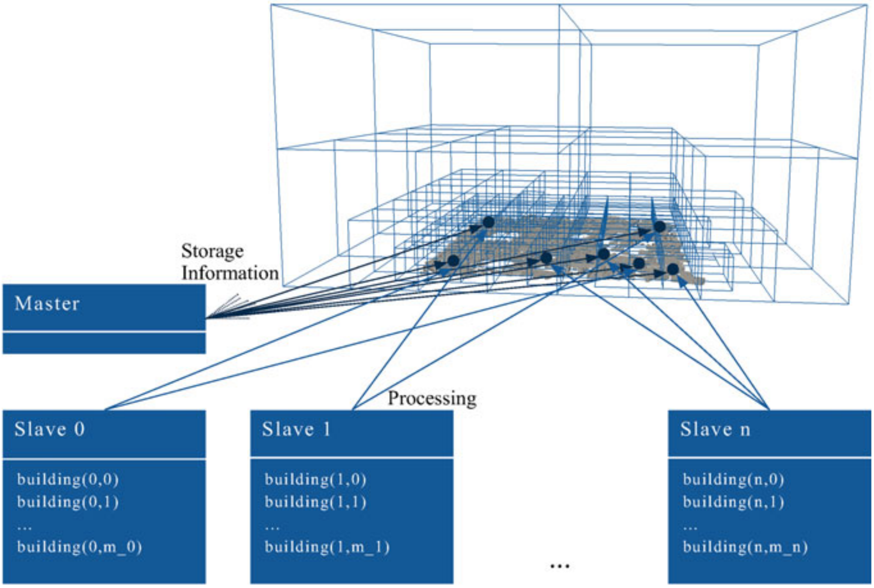

Fig. 4 Parallel processing of product model data via a distributed memory approach (MPI) on the global scale—one master process handling the first level octree assigns product model data to its slave processes for further treatment

processes for further treatment, i.e. for either the visual exploration of these data or the derivation of computational meshes as input for subsequent simulation tasks. Figure 4 shows the principle of parallel processing of several buildings embedded into the first level octree.

The processing of product model data follows the same octree-based approach and is thus called *second level octree*. An octree is now generated from a single IFC model, representing more or less details depending on the chosen resolution, i.e. tree depth d, leading to $2^d \times 2^d \times 2^d$ voxels in case of a fully refined tree.

The second level octrees—in contrast to the first level one—are not persistently stored and solely computed on-the-fly (i.e. demand-driven) subject to proximity reasons for (interactive) visual exploration purposes or level-of-detail considerations for subsequent simulation tasks. For any voxel of the second level octree it can be decided at all times which parts of the IFC model are mapped, i.e. which parts (or semantic entities) of a building are intersected or included by the respective voxel, using unique part IDs (inherited by all of a part's faces describing its geometry) stored along with the voxel data. Thus, there is a strong linkage between the second level octree and the product model, necessary to answer questions concerning insight gained by the numerical simulation and its impact on entities described in the GIS or BIM model.

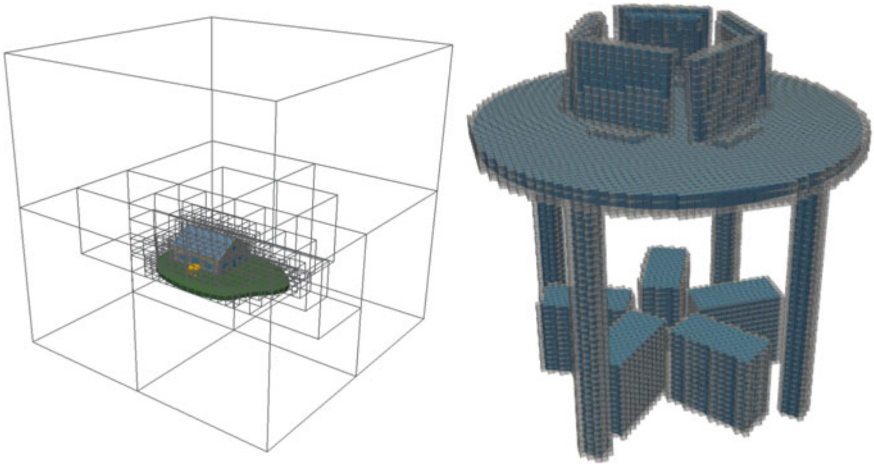

Fig. 5 Examples of a second level octree for a building information model with depth 5 consisting of 84,000 triangles (*left-hand side*) and a derived computational mesh (shown are only cells with flag ‘1’) of auxiliary information located inside a building for a local-scale simulation (*right-hand side*)

As the focus of our approach lies on coupling multi-resolution geometry to environmental numerical simulations, computational meshes of different resolutions representing different subsets of the entire GIS/BIM domain have to be generated. Therefore, users can define a region of interest (cf. bounding box) to select parts of the scene (whole regions, several buildings, or just few rooms of one building) for which a computational mesh shall be derived. The methodological concept is as follows. For each involved IFC model (decided by intersecting the region of interest with the first level octree) a second level octree up to a certain resolution is generated. From these octrees regular computational meshes are derived by further uniform refinements, constituting the entire computational domain. For each cell this computational domain stores its corresponding flag, i.e. ‘1’ or ‘0’, indicating a cell belonging to the geometry (‘1’) or to the fluid part (‘0’). Figure 5 shows a second level octree together with a computational mesh for some sample IFC model. Again we would like to mention, that for any voxel of the second level octree and, thus, also for any cell of the computational mesh it can be retrieved to which (semantic) part of the IFC model it maps, hence an evaluation of simulation results on the product model is possible in order to assess which parts are affected, e.g. by urban flooding, as in our sample application.

As the computational meshes serving as input to numerical simulations can easily exceed several millions or even billions of cells, appropriate sparse storage schemes such as (Pissanetzky 1984; Saad 1992) are of utmost importance. In such schemes, only values different from ‘0’ are stored in a vector together with their respective row and column index of every row sequence of the data.

3 Multi-resolution Parallel Numerical Simulation

During the past years, multi-scale or multi-resolution approaches have frequently been applied in fluid flow applications, see (Grinberg et al. 2011; John and Kindl 2010; Zhao et al. 2004) for instance. Having high-resolution GIS/BIM model data at hand, the novelty of our approach lies in directly coupling these models to fluid flow simulations at different scales (city → building → room, e.g.) and to propagate simulation results back to those models, e.g. for the assessment of possible damage as impact of an urban flooding. As our framework keeps the link between product model data and the corresponding computational grids, any mapping of simulation results to geometric and semantic information of IFC models is easily possible, in order to answer questions such as "*which parts of a building were exposed to flooding*" or "*which electric devices were damaged due to contact with water*".

The simulation of three-dimensional free surface flow is performed by utilising the parallel OpenFOAM solver *interFoam* on some cluster or supercomputer. In order to perform a flood simulation, the three-dimensional incompressible Navier-Stokes equations are applied (Ferziger and Peric 1996). These equations are solved on a regular Cartesian grid (derived from the second level octree), following a Finite Volume (FV) approach. The interface between the gas-phase region and the liquid-phase region is tracked by a Volume-of-Fluid (VoF) concept (Deshpande et al. 2012).

Resolution adaptation increases the accuracy of the numerical simulation by performing a sequence of successively refined simulations, where the results on the coarse scale are projected as initial and boundary condition to the fine scale. Therefore, the simulation on the global domain (typically covering the entire region) is stopped at a predefined time. Then coarse scale simulation values are used as initial and boundary condition for the refined simulation on the local domain (being a subset of the global one, i.e. typically covering few or just single buildings). Special focus has to be put on the correct application of (transient) boundary conditions, as investigated in Varduhn and Parallel (2014).

4 Post-processing—Propagation to Product Model Data

After performing a flow simulation, the quantities of interest (water-level, velocities, pressure, e.g.) are available for all chosen levels of detail. Algorithms for graphical investigation of these results are well known from scientific visualisation, such as isosurfaces, streamlines, slice planes, etc. (Hansen and Johnson 2005).

Due to the linkage (GIS/BIM model data ↔ simulation results) over different scales, a very detailed investigation as shown in Fig. 6 is now possible. Quantities of interest obtained from the numerical simulation can be used e.g. for a protection planning, mapping individual results to relevant entities of buildings, equipment or built infrastructure. Questions concerning damage probability and protection

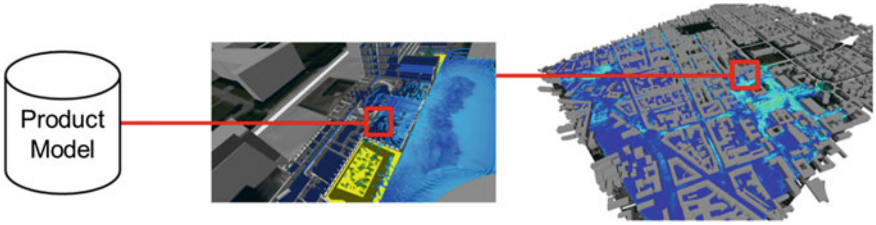

Fig. 6 Linkage between product model data and flow simulation results on different scales—local scale (*middle*) and global scale (*right*)—in order to explore possible flood impacts

possibilities for an assumed flood can be answered in a rational, data and simulation supported disaster management.

The key for this insight is the relation between the second level octree (generated from product model data) and the derived computational mesh as described in Sect. 2. As depicted in Fig. 7, the fluid domain is connected to the structural representation of the product model data, mapping boundary faces of the computational mesh to the construction entities of the underlying product model data. This link is perpetuated throughout the hierarchical approach presented.

Having the results of the flow simulation at hand, simulated quantities are available over the boundary of the computational domain. For CFD simulations, these quantities contain the fluid velocities, the hydrostatic pressure, and water-level. In order to evaluate now the impact of flooding, the following steps have to be performed. If a user wants to estimate the danger for damage of a specific part—for instance some expensive facilities—he can use that part's ID to query for the

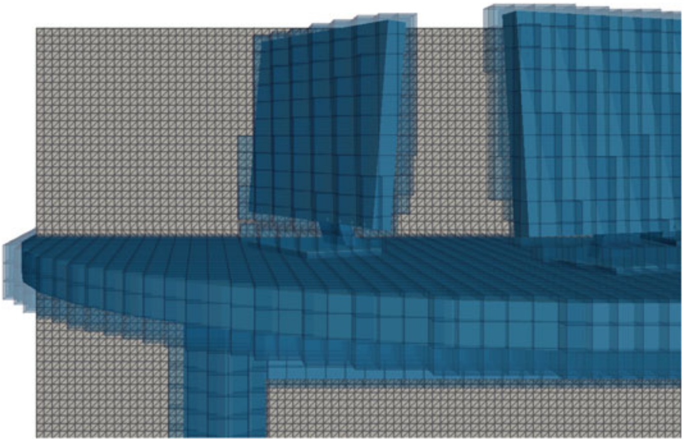

Fig. 7 The computational mesh of the fluid flow simulation can be mapped to the construction details of the product model data. The boundary faces of the fluid mesh are shared with the octree representation of the construction detail. This mapping gives the linkage between simulation results and construction details affected

respective voxels of the second level octree and, thus, the associated computational mesh. Within this mesh, the fluid domain and the voxelisation of that part's faces (triangles) share a common boundary, on which the computed quantities can be evaluated. Thus, the impact of the water to that part can be determined (for instance the expected water-level), and the endangerment can be estimated based on the rich underlying semantics.

In case entities of interest do not exhibit an explicit geometric representation, such as the semantic model 'room' consisting of its surrounding IFC parts wall, floor, and ceiling, those relations have to be established first (see Hitchcock and Wong 2011, e.g.), before being subject to the proposed flood assessments.

5 Urban Flood Simulation with Pipe Network Interaction

The European floods in 2002 and 2013 are examples of devastating impacts on regions, cities, buildings, constructions, and—first and foremost—people affected by them. In May 2013, the Institution of Civil Engineers (ICE) held the ICE Flooding 2013 (Balmforth and Benyon 2013) in order to bring together scientists and researchers to develop flood resilient communities. It is now common understanding that extensive flood simulation will play an important role to achieve this goal.

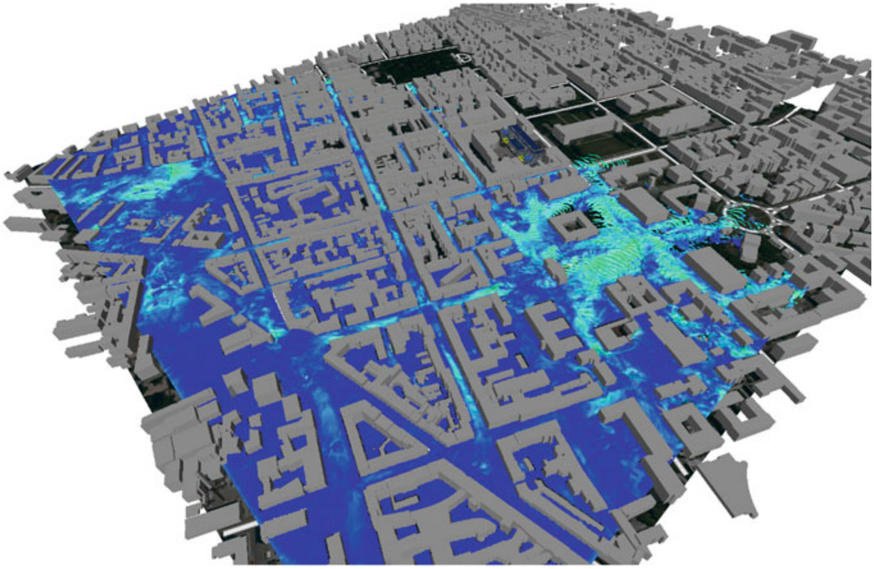

Fig. 8 Flood simulation based on a detailed city model of Munich, visualised using *colour encoded* (velocity) contour surfaces

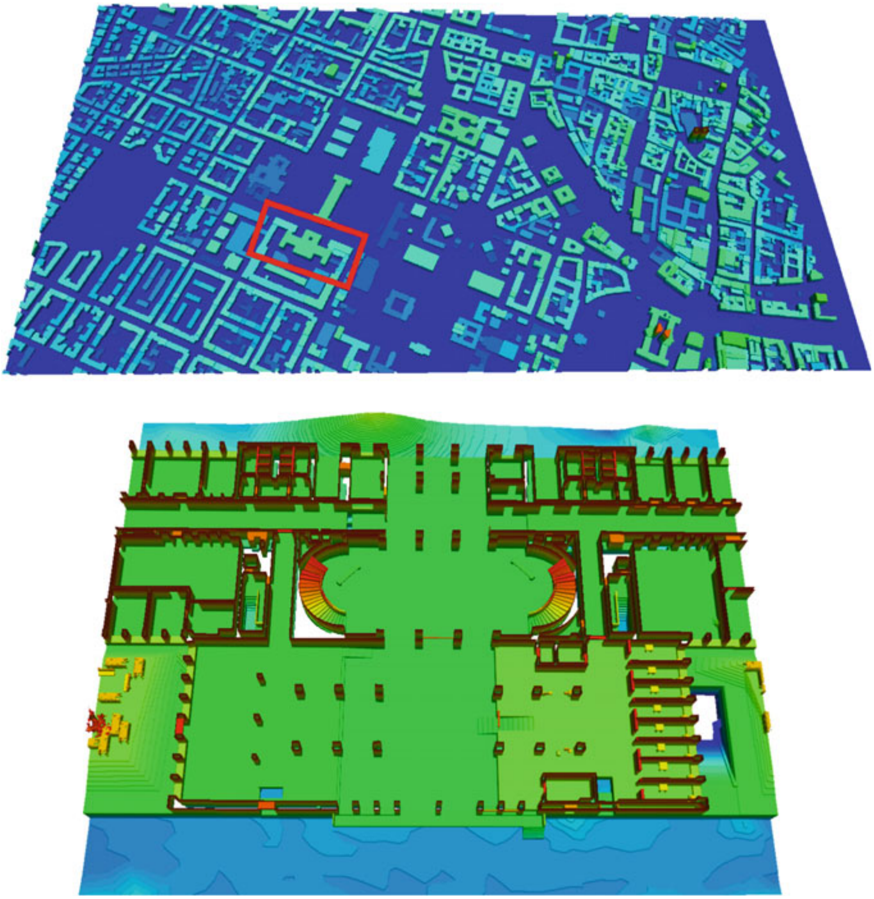

Fig. 9 Computational domain depicted by a contour plot for the global (*top*) and the local scale (*bottom*). The relative height of the surface is *colour encoded*

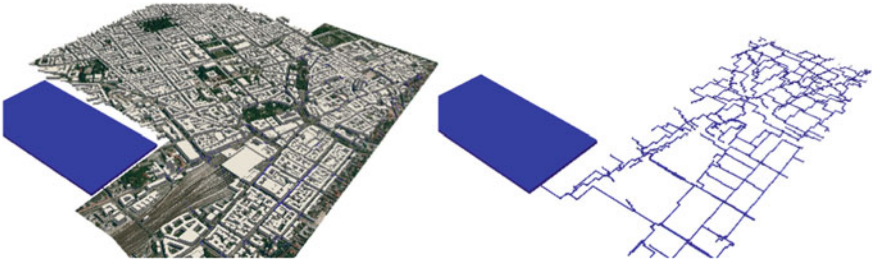

Fig. 10 Modelling a collapsing drainage water system by placing constant hydrostatic pressure (from a fictitious large water reservoir) on one inlet of the network. Initially, the pipe network is assumed to be already flooded

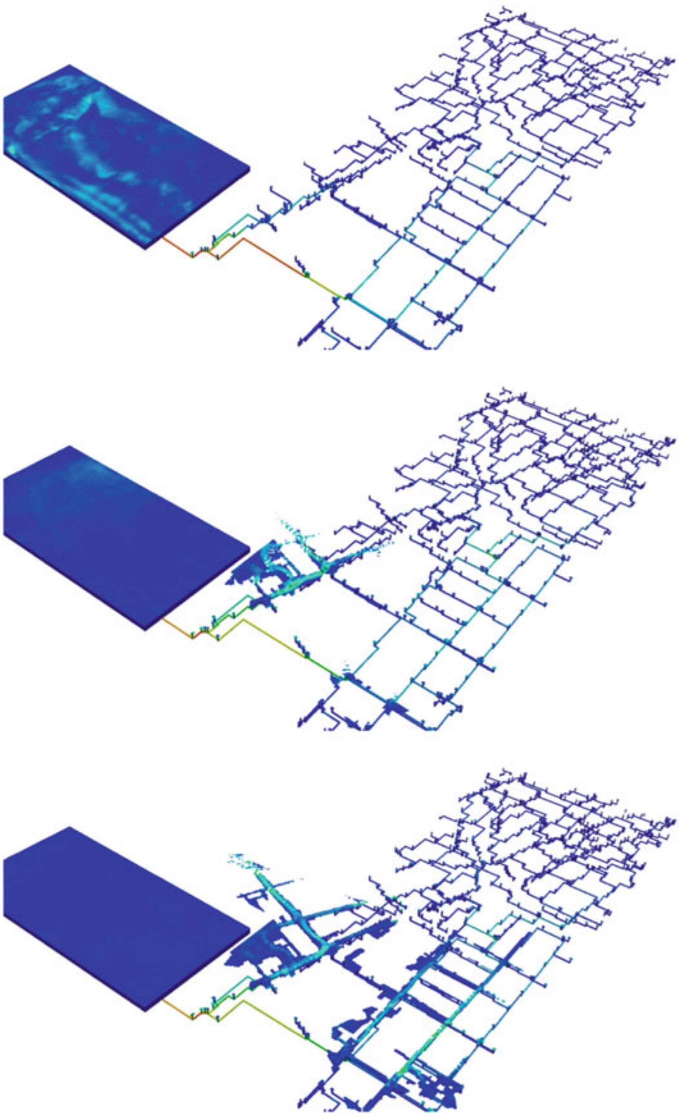

Fig. 11 *Global scale* simulation results of the pipe network and the surface flow—as consequence of a collapsing water drainage system—are shown at different time steps without constructions for better visibility

In the present work we study the interaction of an overloaded pipe network in a city's drainage system and the surface flow following an assumed heavy rainfall. Figure 8 shows the results of such an urban flood simulations.

For this test scenario, a certain region of the Munich City Centre is affected by heavy rainfall, which causes hydrostatic pressure on parts of the rain water drainage

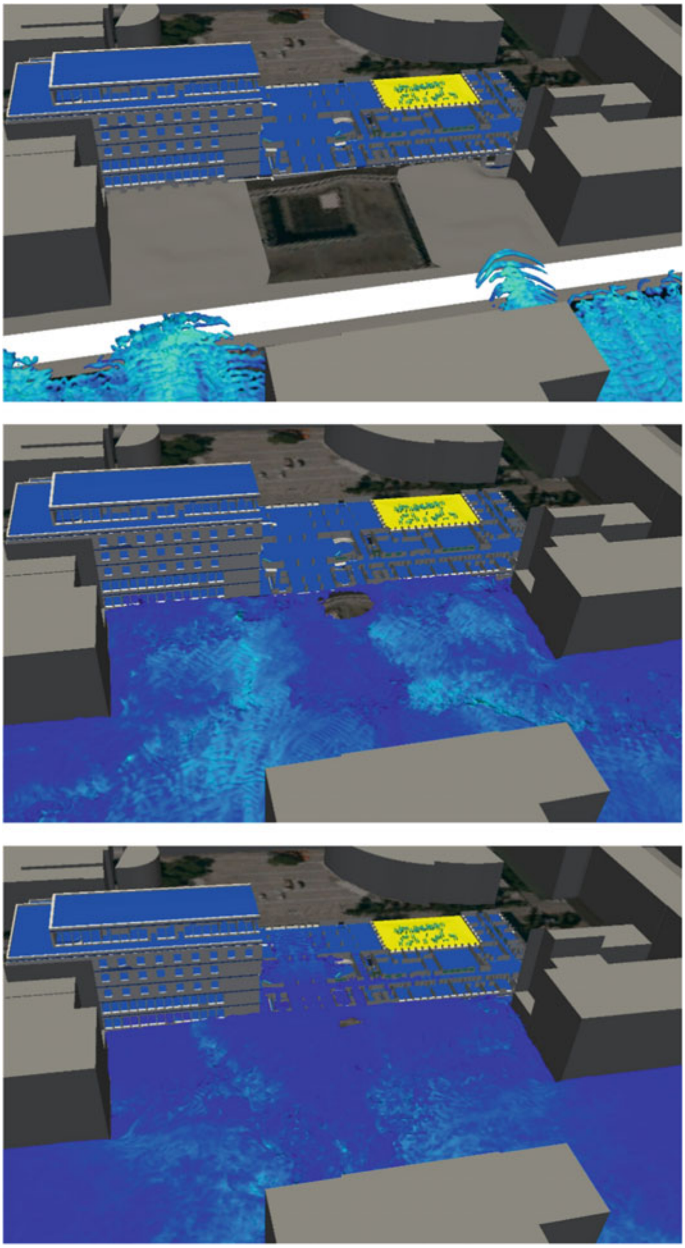

Fig. 12 *Medium scale* investigation of flow behaviour at different time steps on single buildings after first resolution refinement

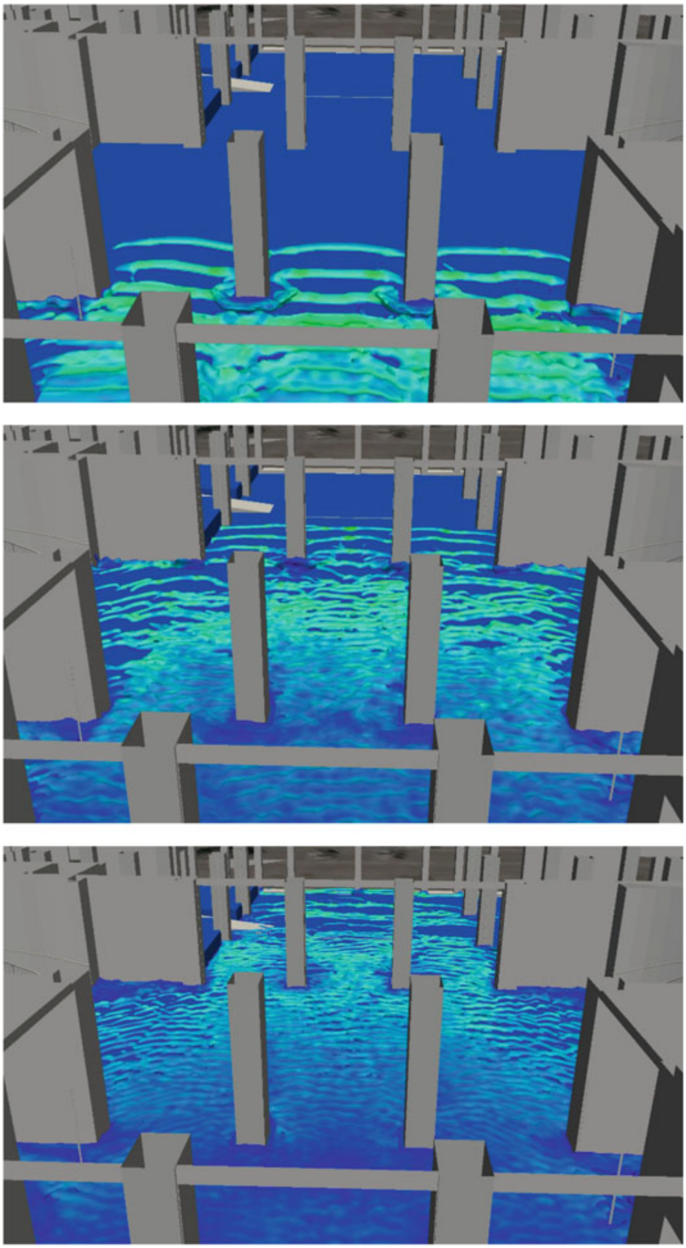

Fig. 13 *Local scale* investigation of flow behaviour at different time steps on construction details after second resolution refinement

system and the sewers in that area. Due to this hydrostatic pressure, the flow in the pipe network evolves and spills parts of the city, even where no or only little rainfall was observed. Using our framework, the flow evolution in the pipe network and on the surface can be investigated, thus allowing a detailed evaluation of areas and buildings affected by floods.

The used GIS and BIM data covers Munich's City Centre including terrain descriptions, models of buildings, and the pipe network. The computational domain is discretised with a resolution of up to 1,800 × 1,650 × 75 voxels, leading to a total of 222.75 million cells. Figure 9 shows a contour plot of the computational domain (boundaries) both for the global and the local scale.

In order to impose the scenario of a collapsing rain water drainage system, the sewer network is given a constant hydrostatic pressure at one of its inlets. This is achieved by placing a large (fictitious) water reservoir over one of the inlets as shown in Fig. 10. It is further assumed that the pipe network system itself is already flooded as an initial condition.

The simulations have been conducted using the OpenFOAM package *interFoam*. In Fig. 11, the results of the pipe network and the surface flow (global scale) are shown. For better visibility, the constructions were removed in order to study flood impacts on the city.

Figure 12 highlights the first adapted resolution refinement for studying the flow behaviour on buildings (medium scale). In Fig. 13, the second adapted resolution refinement is shown, here with projected medium scale results as initial and boundary conditions in order to investigate flood impacts on construction details (local scale).

6 Conclusions

In this paper, we have presented a mashup for the synthesis of high-resolution GIS and BIM data to serve as input for multi-resolution numerical simulations. Due to the hierarchical organisation of the underlying terrain and product model data with a two-level octree-based concept, we are not only able to handle such complex scenes but also to derive computational meshes for subsequent simulation tasks such as urban flooding.

Furthermore, due to the linkage between product model data and the computational domain we can fed back simulation results to IFC models and evaluate the computed quantities on parts of those models. This allows us to estimate possible damage caused e.g. by flood impacts on buildings and built infrastructure in an easy and efficient way. Hence, the shown methodologies can serve and support planers in flood assessments and protection planning. With the extension of pipe networks to urban flood simulations, we have also shown the effective integration of additional data to such multi-resolution computations.

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