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Spatial Enrichment by Applying Hierarchy to Built Infrastructure

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Abstract

This paper shows how hierarchical organisation of data from construction and built infrastructure can help to overcome limitations of nowadays systems that arise from distributed storing and different file formats.

This hierarchy, once established, can then be used to ensure fast access to vast amounts of distributed data and enriches the information basis by spatial context, such that information spread over former distinct storage locations are connected to each other and therefore can be treated in a combined and unified fashion.

Since in our approach an octree structure is used to hold the spatial assembly of the models, many properties such as intersection detection of objects or voxel representations can be evaluated efficiently, to still have access to the original geometry – if necessary – each voxel of the octree stores an additional link to the respective CAD entity.

Keywords: spatial augmentation, built infrastructure (BIM/IFC), hierarchical data structures, computational steering, parallel computing, visibility analysis, proximity analysis.

1 Introduction

Today, the need for digital information from built infrastructure is dominating many tasks within civil engineering such as planning or maintenance and it is still growing rapidly. In many cases the entirety of those information is not (cross-)linked over domains or scales, and, thus, prevents to gain a better insight and deeper understanding of the underlying data. To provide the advantage of hierarchical ordered information, it has to be dealt with data existing at different scales and models respecting the amount of data and their structure, which requires the application of appropriate hierarchy and usage of elaborate techniques.

In this paper, we present an approach for the hierarchical organisation of varying information such as textured height maps for terrain visualisation [1] or built infrastructure using Industry-Foundation-Classes (IFC) [2] providing geometric and auxiliary information at fully detailed level. The objective is to enhance the gain of insight to the user by fusing and exploiting these diverse data. Such an aggregation is the basis for arbitrary queries, for example the embedding of graph theory to building information modelling, and enables the separation of certain information from unnecessary overhead.

In our approach, we apply a hierarchical data structure by using octrees in order to bridge the gap between different models and varying scales of information. This hierarchy, once established, provides an efficient tool for handling varieties of information and evaluating global specific values necessary for the orchestration of the models such as neighbouring relations between objects or calculating characteristics such as the total amount of floor space in a whole borough. By doing so, we overcome the obstacle of (distributed) information being separated or only weakly associated and therefore receive meta-information which in that form is not available within the single data sources.

As example, we show the coupling of a thermal comfort assessment analysis using this octree to a zonal model approach or a CFD simulation. Thermal comfort is defined and the coupling procedures will be described in detail as well as underlined by results of such a computation.

This paper is organised as follows: In section 2, we give an overview of the design and the implementation of a framework whereas in section 3, an example for the hierarchical organisation of constructions and built infrastructure is presented. In section 4, the application of our framework to a numerical simulation is highlighted before in section 5 we close with a short conclusion and outlook.

2 Outline of the Implemented Framework

In this section, we give an introduction to the requests and the resulting design decisions for the implementation of our framework.

In a first step, a file format for storing and accessing the models of constructions and built infrastructure had to be chosen. Two main properties can be identified to be mandatory for a file format to be suitable for our purposes. First of all the, format has to be capable of providing geometric and auxiliary information at fully detail. Detailed geometric information is mandatory for processing models on a very fine grain exploration even down to the level of screws. Auxiliary information delivers the mapping between the geometric representation of an object and its function in the construction or built infrastructure, this ranges from specification of all doors or windows in a model to the free association of attributes such as the isolation factor of the glass used for a window or the service interval of an elevator just to name a few.

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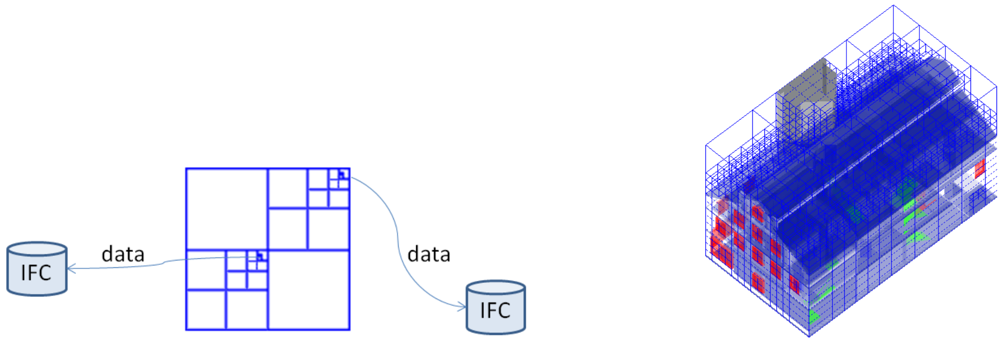

Figure 1: On the left-hand side, a 2D-projection of a sample first layer octree ensuring global location awareness is given, whereas on the right-hand side a dynamic second layer octree based on a building is shown (pictures taken from [4]).

Second, this file format has to meet an industry standard in order to ensure a general interoperability of the framework with existing solutions. It turned out that Industry-Foundation-Classes (IFC) [2] fulfil this criteria and therefore have been chosen and integrated into our framework.

As our framework bases on the idea of integrating various types of data, in a next step the capability of terrain rendering was added, one of the techniques used in the field of geo-information systems. Therefore, we use a digital height map delivering the elevations of a terrain by providing the z–coordinate on a regular grid. From this we are able to construct a triangular mesh and perform an orthogonal projection of the texture of the region onto it. Hence, we receive a realistic three-dimensional representation of the surface for visualisation purposes and the data basis for engineering tasks such as road planning [3] or reasonable boundary conditions for large scale flow simulations as presented in section 4.4.

The hierarchical organisation was the main part of our work during the framework design as it had to fulfil multiple requests. Thus, we are focusing on large sets of constructions and built infrastructure models in the size of cities, regions, or even countries. The underlying data structure then arises the necessity of being capable to store vast amounts of information on the one hand, and to provide fast access to these information on the other hand. Furthermore, this data structure has to provide a hybrid setting in the meaning that it delivers the composition of all data of our domain by still being capable of accessing the fully detailed data basis of the framework for highly specific values on very fine levels. As already mentioned before, this induces the representation to be approximative to some extend which is negligible in our setting. The octree provides an inherent level of detail capability, since regions that are lying far away from the user are not resolved to full depth and will be locally refined on demand. Due to these demands we decided to implement an octree consisting of a two layer fashion, see figure 1. The octree is a based on the principle of recursive spatial decomposition as it divides the domain along every axis in two equal parts and applies to each of the resulting eight sons (octants) this decomposition, until the object

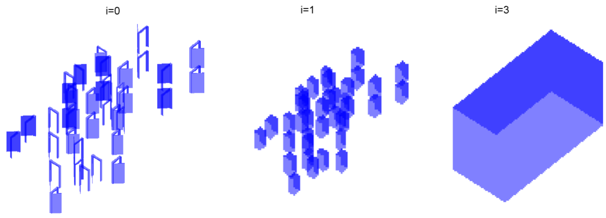

Figure 2: The extraction of doors for illustrating a step wise coarsening due to different levels of detail (pictures taken from [4])

is completely contained in the octant or does not intersect, or a predefined maximal depth is reached. On a first layer we hold a precomputed octree which assembles all models based on their bounding boxes in order to provide global location awareness, based on a varying set of dynamical on-the-fly generated second-layer octrees, each holding exactly one building with its exact geometric representation and auxiliary information.

For reasons of completeness we want to give a short look at the remaining tasks for the set up, which arise from the pure amount of data to be processed by the framework. In a first step, several levels of detail (LoD) have been identified and implemented, see figure 2, which uses the fact that with increasing distance, visualisation details can be step wise coarsened without an observable loss of information. Initially elements such as windows or doors are approximated with their bounding boxes as on still further distances, complete buildings can be visualised via their bounding boxes and for a street or a bridge the representation by a single line is sufficient.

On all levels of detail, a visibility analysis helps to reduce the amount of primitives to be rendered as far as possible. Since modern hardware is nowadays shipped as multi-core systems, parallelisation techniques have been applied to the algorithms presented in this section to exploit the full performance of the hardware using OpenMP [5]. The synchronisation of the single processing threads could be ensured by using the structure of the octree on both layers of its implementation. Since this is just a short introduction to the technical implementation, we refer the reader to [4] for a deeper look into detail.

3 Applying Hierarchy to Constructions and Built Infrastructure

In this section, we discuss the hierarchical organisation of IFC based models for constructions and built infrastructure. As already mentioned during the introduction of our framework in section 2, we have chosen octrees for the implementation.

For building up the data basis of our framework we start with a set of N IFC models which are extracted by using the 3rd-party tool IFCEngine [6]. As IFCEngine provides the full detailed geometry, we can directly generate the bounding box for each construction and build up the first-layer octree based on the distinct bounding boxes for all constructions and built infrastructure. As we still keep the (physical) storage information of the model in the respective leaf node, it is possible to query the IFC information of a model at any time.

The generation of the second-layer octrees for each single IFC model is a highly dynamical process, as it is completely driven by user interactions. For every change of the position of the user or its viewing angle, we identify by querying the first layer octree which models have to be loaded, refined, or can be discarded. If a model has to be loaded, IFCEngine is used to receive its triangular representation and the octree is built up based on the full detailed information. We want to point out that the information about a model retrieved from IFC are not restricted to the geometric representation but also contain the complete set of auxiliary information of this model.

With the hierarchical organisation we have established a foundation resulting from different formats and scales that is capable of orchestrating large sets of information and gives the user a tool at hand to answer new kinds of questions taking into account data that cover a whole city or even a region and can rely on information in any depth.

4 Use Cases

In this section, we show some sample use cases for the application of our framework, whereas we want to demonstrate the possibility of evaluating information on a huge scale without being restricted in the considered depth of information, which is a new approach beyond nowadays existing solutions.

4.1 Application to Planning Processes

In this section, we focus on the planning process of large constructions in dense regions or regions with critical parameters.

In a first stage of planning a highway, e. g., it is mandatory to check the intersections of the new construction with existing constructions or built infrastructure such as pipe networks, streets or buildings to analyse possible construction scenarios.

When adding a new construction to the existing set of constructions, it is first of all treated as every other object in the set. As described in section 3, the octree is generated based on the models added to the framework. Accordingly, we can focus on exploiting the data structure and, thus, checking for intersections between models can be reduced to a fast and simple multiplexing of linearised octrees.

A linearisation of an octree is a bitwise representation of the tree, see figure 3, based on the information if an octant is refined or not. Initially, the first level of the tree is linearised by iterating through its octants in an arbitrary but fixed order. Leaf nodes add a 0 to the stream followed by its (fixed sized) value, further refined octants add a 1 and the recursive linearisation of their eight sons in the same order as before.

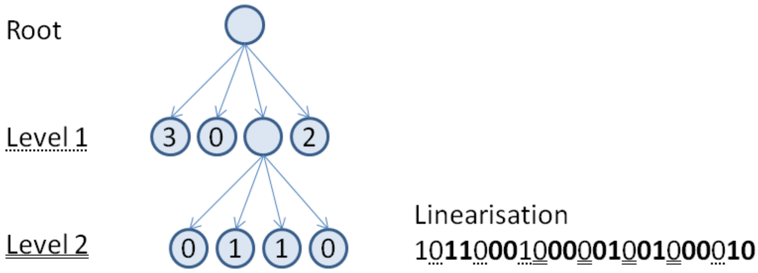

Figure 3: A quadtree, the 2D equivalent of an octree, and its linearisation with the values of the leaf nodes (0) stored in binary representation and highlighted bold.

Concerning the application of our framework to planning processes, only the linearisation of the octree, holding the new construction, has to be multiplexed with the linearised octrees of the objects in the domain to detect intersections. Multiplexing in this context describes the parallel iteration through both streams and checking a logical operator on both streams, see figure 4 and [7].

Multiplexing two streams with the logical operator AND of one octree specifying the new construction and another octree holding the domain it is planed for, delivers all intersections of the two groups of objects by simply iterating through two bit streams. Therefore, the octree structure does not have to be re-established. Instead, intersection detections can be made only by iterating through the streams, although the octree structure can be retrieved from its linearisation by simply pushing the linearisation level-wise onto a stack.

As during planning processes the check of intersections is a highly dynamical process, these interference checks can be performed in en efficient manner by applying multiplexing to the linearisation of octrees, since the domain where the construction is intended to be planed for stays constant, its linearisation stays constant as well and therefore only the octree of the new construction has to be recomputed or even only locally refined.

By performing interference checking based on multiplexing, sufficient update rates

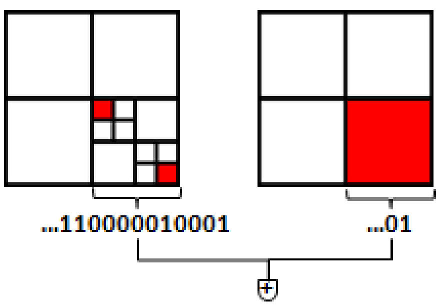

Figure 4: Parallel iteration through two linearised octrees of different depth.

can be achieved even for wide ranging constructions and therefore enable the user to perform computational steering for planning processes. A good estimation for the time consumption of multiplexing octrees is given in [7], whereas in our case only one tree for the new construction is multiplexed with the set of N octrees, thus, the complexity of the problem reduces from the type of $\mathcal{O}(N^2)$ to $\mathcal{O}(N)$.

4.2 Global queries

In this section, we describe the evaluation of global queries based on fine detailed information concerning constructions and built infrastructure. The application of these queries are lying in many fields besides civil engineering such as environmental engineering [8] or disaster management [9] where complex queries have to be evaluated in short time.

In the situation of an earthquake for example one of the first things that have to be done is to establish medical support centres. This complex task can at a first stage be split into a query connecting spatial questions with auxiliary information provided by IFC models.

In this case, a query can be specified as the search for the closest buildings with a specified minimal distance to the epicentre, which has to be equipped with an air condition system and an amount of usable space of at least 1000sqf. The evaluation of such a query can be done by first evaluating the hierarchy of models and filter buildings that are candidates due to their relative position to the epicentre. In algorithm 1, the pseudo code of such a query in SQL similar syntax is given, for further approaches see [10]. These candidates are then iterated and due to the underlying fully detailed IFC information, containing search criteria such as air condition systems or the amount of usable space, they can be evaluated and ranked.

By performing this search driven by the spatial data structure, first results close to the actual point can be evaluated and processed with IFC information, whereas the iteration through the data is extended while delivering these results to the user.

At the moment the definition of the input format of queries is still subject to current work to give the user a tool at hand which lets him freely perform questions to the framework.

Algorithm 1 Pseudo code for a query combining spatial and IFC criteria

```
SELECT * FROM buildings
WHERE (IFC_has_AC = TRUE AND SUM(IFC_floor_space) > 1000)
ORDER BY DIST(my_position - center) ASC
```

4.3 Application of Indoor Thermal Comfort Assessment for Buildings

In modern design and planning processes of large buildings, indoor thermal comfort assessment is mandatory. Ideally an assessment should be done in a very early design stage as economic savings have in this phase the highest potential due to the possibility of changing design steps easily.

ASHRAE Standard 55 [11] defines thermal comfort as a ‘condition of mind that expresses satisfaction with the thermal environment’. Benzinger [12] defines thermal comfort as ‘the absence of driving impulses from cutaneous and hypothalamic receptors’. Obviously, thermal comfort is related to temperature distribution in rooms as well as temperature sensation and comfort perception. Therefore, it is strongly related to a thermal state of the body itself which is a result of thermophysical and regulatory processes of the central nervous system (CNS). Furthermore, there is a varying influence of single body parts which need to be weighted with different factors according to their specific physiology. The most significant factors for temperature sensation are the deviation of the mean skin temperature from a setpoint ($\Delta T_{sk,m}$), hypothalamus temperature deviation from a setpoint (ΔT_{hy}) as well as the change of mean skin temperature over time ($\mathrm{d}T_{sk,m}/\mathrm{d}t$).

One way of assessing indoor thermal comfort is using diagrams given in international standards such as EN ISO 15251 [13] or EN ISO 7730 [14], e. g. Usually the analysis takes into account the indoor operative temperature and the running outdoor temperature. The indoor operative temperature according to the ASHRAE handbook of fundamentals [15] can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. The running outdoor temperature is defined in EN ISO 15251 [13] by using an exponentially weighted average of the mean outdoor temperatures of the last seven days. Very high or very low peaks are smoothed out in this consideration. Statistical weather data from the specific location of the building itself need to be used for these computations. According to the settings of this two values, the room in the building can be classified into three categories of thermal comfort (I to III). The categorisation also depends on the type of building and usage. If users are allowed to open windows and apply a self-regulation, different category boundary conditions are applied than in the case of mechanically ventilated buildings with no user regulation or the possibility to open windows. These classifications are done on a large scale, regarding the room itself and using empirical diagrams from standards.

Increasing the amount of details, the analysis is extended to user level. As very easy model, the predicted mean vote (PMV) model was proposed by Fanger [16]. It is valid for uniform, steady-state boundary conditions for the whole body near thermal neutrality and computes the imbalance between the actual heat flow from the body and the heat flow required for optimum comfort. The result is interpreted on a 7-point ASHRAE [15] scale where -3 denotes very cold, 0 means neutral and $+3$ denotes a very hot state. Using the predicted mean vote one can compute the predicted percent-

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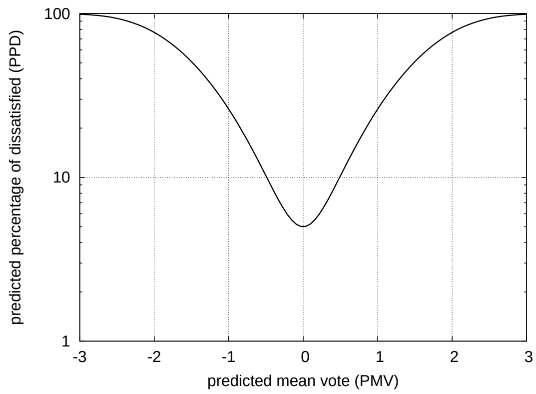

Figure 5: predicted percentage of dissatisfied (PPD) [14]

age of dissatisfied (PPD) by the relation

$$\mathrm{PPD} = 100 - 95 \cdot \exp\left(-0.03353 \cdot \mathrm{PMV}^4 - 0.2179 \cdot \mathrm{PMV}^2\right) . \tag{1}$$

As one can expect, 100% of satisfied people can never be reached, and the formula shows this fact while observing the minimum of the PPD function resulting at 5% for $\mathrm{PMV} = 0$ (see figure 5). Unfortunately the boundary conditions for which the predicted mean vote model is applicable are quite restricted. During a dynamic transient simulation, the boundary conditions are not steady-state and if local effects such as asymmetric thermal radiation are applied, the boundary conditions are not uniform either. Furthermore, only one global value is computed for the body which is unable to cover local thermal effects. Therefore other models need to be applied.

Local thermal effects consider draught, vertical temperature gradients, warm and cold floors, as well as asymmetric temperature radiation. Considering a test subject in a ventilated room, local effects such as vertical temperature gradients and draught differences between the different body parts have to be taken into account. Therefore other models than the one of Fanger must to be applied. The 65MN model of Tanabe [17] or the model of Fiala [18, 19, 20] based on the work of Stolwijk [21] can be used, as they can account for local thermal effects. With these models, local resultant surface temperatures can be computed and linked via local thermal sensation votes (LTSV) to a local perception of comfort regarding all boundary conditions as described by van Treeck et al. in [22]. A result of an example simulation can be seen in figure 6.

Boundary conditions from the room itself as well as weather data and other occupants will influence the simulation of one manikin. As the manikin itself will also influence the room, a bidirectional coupling needs to be established. If the room is large compared to the manikin itself, only a unidirectional coupling can be applied, ignoring the influence from the manikin to the room.

As seen above, for all kinds of thermal comfort assessment (standard-based or manikin-based) surface temperatures of the room itself are necessary as assessment

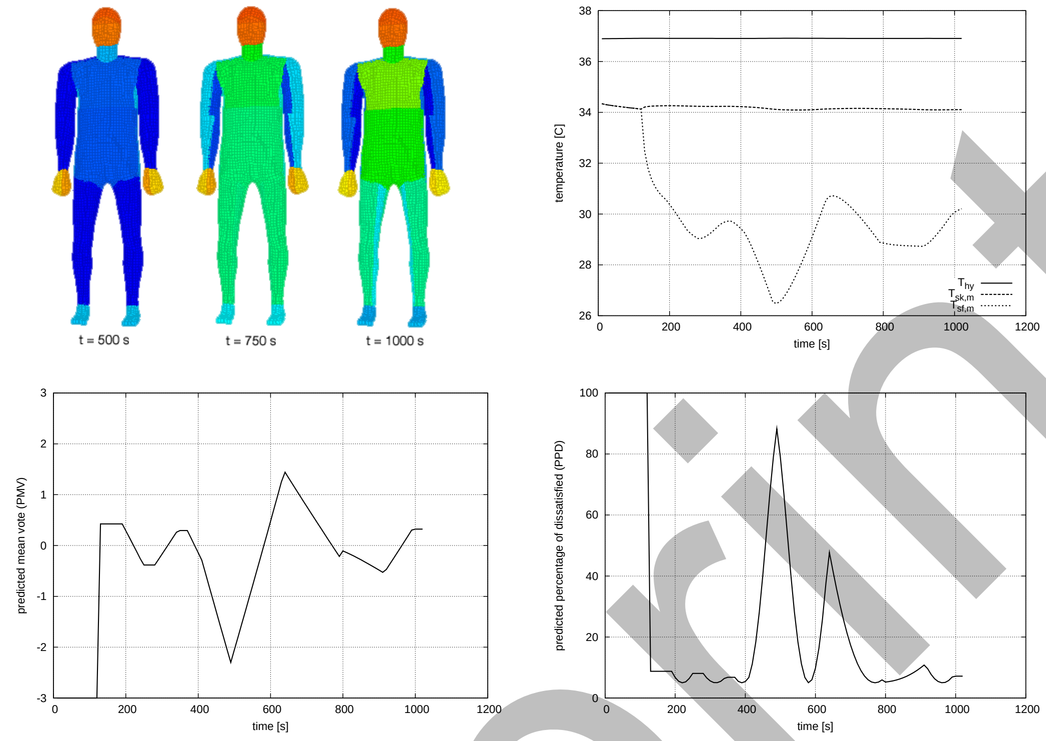

Figure 6: Thermal comfort assessment using the model of Fiala: upper left part shows local surface temperatures of all body parts at 3 different time steps with a fixed linear scaling where blue is 26°C and red is 37°C; the graphs show the results of the simulation. The upper right part shows the temperature graph containing the hypothalamus temperature T_{hy}, the mean skin temperature $T_{sk,m}$ and the mean surface temperature $T_{sf,m}$ on the outside of the clothing.

condition. Therefore some kind of thermal simulation has to be applied.

Three types of simulation are applicable, ranging from a very large scale in time and space to a very small one. An annual or monthly balance can be used by computing a stationary heat balance over a long period in time. This is a very coarse method and only mentioned here for reasons of completeness. Another method is the simulation of a thermal multi-zone model where a quite coarse discretisation in space, but a fine discretisation in time is selected. A room is represented by a minimum of one node (single-zone model) for the air temperature etc. The model is based on an anisotropic finite volume conservation approach explained in Clarke [23]. The physical problem is expressed in a set of conservation equations for energy, momentum and mass, which are solved for each time step resulting in the temperature values in each degree of freedom such as the air and wall surface temperatures for instance. The numerical validation of the zonal model used for this work can be found in [24]. Another method for computing the surface temperatures is the computational fluid dynamics approach discussed in section 4.4.

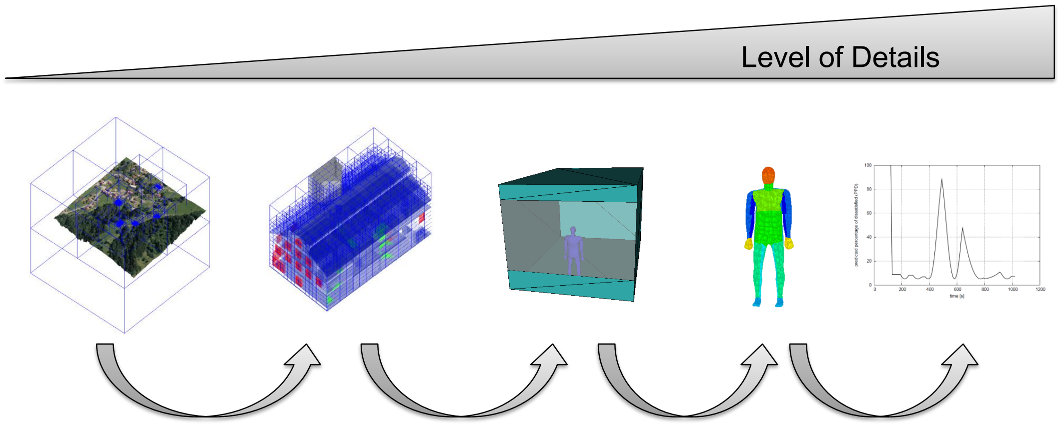

Figure 7: level of detail dependent analysis gathering data from every step

The zonal computation for simulating the resultant surface temperatures in each time step needs beside the weather data, including the direct and diffuse solar irradiation, the air temperature, and the wind velocities, a complete geometric description of the room or the building to simulate, including detailed information about the construction parameters applied to this specific building. Here we can take advantage of the combination of the hierarchical data structure delivering the assembly of the models the framework is based on, and the specific information depth provided by the IFC. On the one hand, we receive from IFC the definition of rooms, floors, etc. referred to by the IFCSPACE [2] definition, which directly provides the geometric definition of the domain we are covering with our analysis. On the other hand, we can take advantage of the capability of IFC to deliver auxiliary information related to single parts of a construction. These input data range from the isolation values of the glass of a window pane to the surface condition of walls with all its layers or the carpet a room is equipped with. An example of this procedure can be seen in figure 7.

Using all these embedded information sources, a nearly automated whole year simulation can be done and a thermal comfort assessment analysis can be applied consequently.

4.4 Application of Computational Fluid Dynamics

This section focuses on applying CFD simulations on varying scales by using a Lattice-Boltzmann (LB) implementation [25, 26] existing at our research group. Unlike the classical method using the Navier-Stokes-Equations, the Lattice-Boltzmann equations are based on concepts of statistical physics. They use a first order finite difference approach in space and time resulting in a quite simple scheme regarding implementation. For additional numerical stability of the method, a multiple-relaxation-time (MRT) model based on d'Humières [27] was used and the simulation of convective airflows was achieved by using the hybrid thermal model proposed by Lallemand &

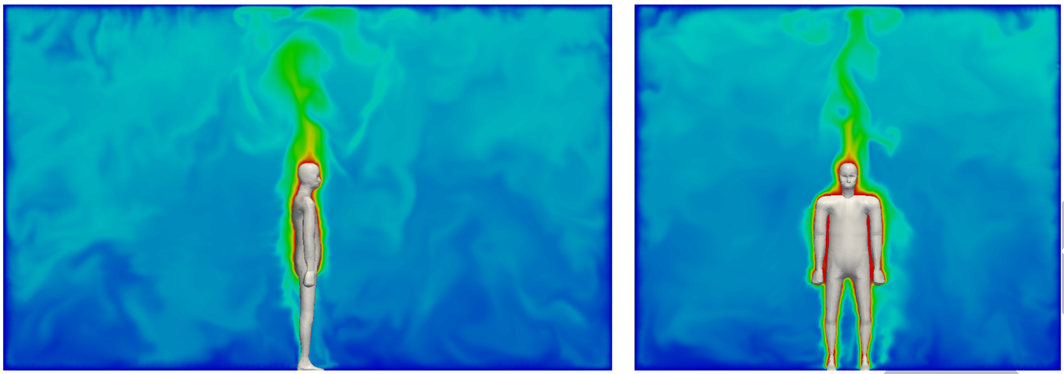

Figure 8: Temperature field resulting from a CFD computation of natural convection phenomenon of a human test subject in a room after 300,000 time steps

Luo [28]. For a deeper look into detail, the user is referred to [29, 30, 31].

As input data for such a Lattice-Boltzmann method, a voxelised structure containing boundary condition information is necessary. Based on the hierarchical representation we can exploit the spatial decomposition structure of the octree already at hand to generate a voxel representation of the domain of interest as input for the CFD simulation. This is done by adjusting the depth of the octree to the defined mesh width of the CFD simulation and export the octree in a way that in opposite to a basic octree implementation even black nodes, meaning octants that are completely contained in an object, are refined to the predefined depth. Therefore, we receive a complete equidistant voxel representation of the considered domain to hand over to the CFD simulation after mapping and setting the adjusted boundary conditions. An analysis regarding the parallel performance of the used code and the influence of different discretisations can be found in [25].

Figure 8 shows the results of a Lattice-Boltzmann computation using the parallel code mentioned above. The computation was done using approximately 26.9 million voxels and 128 computation nodes, and took for the given temperature boundary conditions around 24 hours for computing and writing detailed information for 300,000 time steps. Unfortunately this computation represents only a few seconds of real time behaviour, so a whole year computation of a complete building or a city is at the moment not feasible. For this type of simulation, a zonal approach using empirical convection coefficients, coupled with a CFD analysis at critical time steps for checking the behaviour of the flow is a reasonable approach of a complete thermal assessment analysis.

5 Conclusion

In this paper, we presented an approach for using the concept of hierarchical organised information with its application to data from constructions, built infrastructure, and terrain data. Hence, the user is given a tool at hand which combines fast access to the fusion of vast amounts of information processing at arbitrary depth of detail. This framework is open to be enriched by further formats or data repositories in general, as planed for future work.

In contrast to existing frameworks the application of a strict hierarchical concept overcomes the limitations of distributed stored information without omitting the full depth of information or efficient data access and processing.

Future work will comprise the integration of further data formats such as volumetric subsurface data, simulation results, and seismic data. Besides this, the support of computational steering capabilities, i. e. interactive computing, will be promoted and an interface for running utmost free queries against the data basis as described in 4.2 will be incorporated.

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