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PEDESTRIAN SIMULATION BASED ON BIM DATA

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ABSTRACT

This paper presents an extension of the standardized Industry Foundation Classes (IFC), in order to capture the input data required for performing pedestrian simulations. Pedestrian simulations can identify potential threats already in the design phase of a building and evaluate protective measures. The BIM model serves as a central structure, which is going to be optimized by simulations (cf. figure 1). The building design is validated by a pedestrian simulation against performance indicators like the overall evacuation time or densities inside congestions. In order to improve the corresponding performance of the building, the simulator can automatically optimize relevant features of the BIM model - like door openings and wave breakers. After a review by the architect or engineer, the changes can be directly transferred to the model. Pedestrian streams turned out to be a limiting factor for building safety, particularly regarding emergency evacuation and the capacity of critical elements like stairways, escalators and elevators.

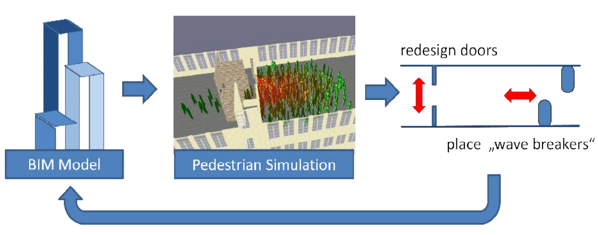

Figure 1: Building design supported by pedestrian simulations

In addition, the pedestrian model can utilize information of the BIM model during operation. For example, in case of a fire, the simulator imports the position of the fire detectors from the model, queries its state from the Building Management System, and in turn can calculate safe egress routes for the occupants.

INTRODUCTION

A BIM model is a comprehensive digital representation of a building, comprising not only the 3D shape of all building elements and enclosed spaces, but also their semantics including their attributes and the relationship among them (Eastman et al. 2011). BIM technology has been developed to overcome weak software interoperability by providing a vendor-independent neutral data format, supporting the entire lifecycle of a building and integrating the different disciplines involved. This data format is called Industry Foundation Classes - IFC (Laakso & Kiviniemi 2012, Liebich et al. 2013). The technology of Building Information Modeling (BIM), which is based on a comprehensive digital representation of buildings and facilities, provides an excellent basis for integrating building design with egress simulation while avoiding laborious and time-consuming manual data transfer.

Since the design of a building significantly influences the safety of its occupants, safety regulations should be checked in all stages of the lifecycle of a building. As an important means of assessing the safety of a building, we have developed a simulator to analyze pedestrian streams under various hazardous conditions (e.g. emergency evacuation, fire and smoke, Mayer et al. 2012). In order to evaluate pedestrian streams during all stages of the building development (planning – construction – operation – refurbishment), the simulation is based on building data from a BIM server or a BIM / IFC file. Currently, the usage of a BIM model is restricted to the extraction of walls and obstacles (like furniture) for the simulation environment. We propose an extension of the BIM standard by typical simulation elements like walkways, gathering points or turnstiles. In addition, we propose a normalization of certain BIM elements in order to render them compatible for the import into simulation tools. Examples are standards for the concatenation of walls and the improved identification of stair properties, like the connection to levels, steepness and number of stairs or inclination.

As mentioned above, pedestrian simulation is an essential tool, applicable during the whole lifecycle of a building, not necessarily limited to the planning phase. If construction stages are represented in the BIM model, the pedestrian simulation can improve the safety of building workers (emergency evacuation based on current construction stage). Later on, the pedestrian simulation can be linked to a building management system (BMS) in order to allow for a situational intelligent evacuation planning. This could be done during partial renovations of the building or during planned events, where a temporary accumulation of people emerges. Additionally, since the evacuation simulation will be based on an advanced BIM model, changes in the model will be automatically reflected in the evacuation system of the building (if the BMS is connected to dynamic evacuation indicators like dynamic exit signs etc.). Therefore, by linking a pedestrian simulation system to a BIM model, the simulation becomes an integral part of the building lifecycle management and allows for an abundance of new applications.

SIMULATION

Simulation Paradigms

The purpose of a pedestrian simulation is to measure the distribution and flow of persons within a given area during a time interval of interest. Depending on the spatial discretization of the simulation area, we can distinguish two different types of pedestrian simulation models: microscopic and macroscopic models (Schadschneider et. al. 2009). A microscopic simulation is able to generate movement of each pedestrian separately. Pedestrians interact with each other and are guided along static obstacles within a simulation scenario. Thus, in microscopic models a minor change in the simulation's spatial layout can induce a huge difference in the movement patterns of the generated pedestrians. This is particularly helpful to check for crowd phenomena like congestions, lane formations in counterflows, oscillating pedestrian flows at bottlenecks or herding behavior (Helbing et. al. 2002, Schadschneider et. al. 2009). In contrast to microscopic models, a macroscopic approach is restricted to the calculation of flows at certain areas, modeled as a network graph. Macroscopic models hide many details, e. g. cannot distinguish between individual pedestrians, but compared to microscopic models they are able to provide mathematically closed solutions for interesting indicators like egress time (Hamacher and Tjandra 2002). Additional to the mentioned simulation models, recently researches investigate agent-based microscopic models (Pan et al. 2007) and hybrid models (Borrmann et al. 2012, Kneidl et al. 2012, 2013). However, if performance matters, macroscopic models are in favor, while only microscopic simulations can provide information on all levels of detail.

Regarding the modeling of the simulation area, two different approaches for microscopic simulators can be distinguished, discrete and continuous. In the discrete case, simulators operate on a fixed spatial grid and fixed time steps. On the contrary, in continuous simulation models, pedestrians can be positioned on arbitrarily locations, thus continuous time steps can be chosen (Schadschneider et. al. 2009). Due to their nature, discrete simulations are mostly modeled by cellular automata (Blue and Adler 2001). However, some continuous models can be restrained in order to yield a discrete simulation (Seitz and Köster 2012). While discrete simulation comes with a better performance (Blue and Adler 2001), continuous approaches provide a more precise representation of pedestrian's movement trajectories (Lerner et. al. 2007).

Our use cases are focused on office buildings and campus scenarios. This requires an approach, which is able to create fine pedestrian interactions and also performs well on rather large simulation scenarios. Therefore, a discrete microscopic simulation paradigm fits our purposes best and a cellular automata was implemented as simulation model.

Simulation Model

The simulator implements a discrete, microscopic model for the movement of pedestrians. However, the behavior of a single individual can never be anticipated, but the interaction of many individuals can be emulated by microscopic simulation. The example shown in figure 2 clarifies this concept: the leftmost room is evacuated through a narrow door. By means of a microscopic simulation, the positions of individual pedestrians are calculated. Each of the occupants is represented by a filled circle in the picture, where the color of the circle indicates the density of the crowd. Reddish areas may indicate issues of the building's layout. In contrast, the position of the individuals is of minor importance in macroscopic simulations.

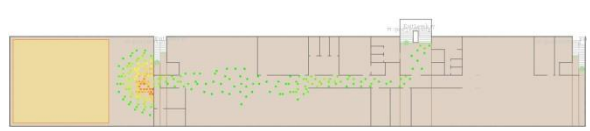

Figure 2: Evacuation Simulation: occupants are generated at a source (yellow rectangle) and are guided to the exits (via the stairs)

The implementation of the pedestrian simulation is based on a cellular automaton, which operates on a hexagonal grid. The pedestrians are passive elements (in contrast to agents), which are moved from cell to cell after an equidistant, discrete amount of time. The movement of pedestrians is influenced by an approach based on potentials, where pedestrians are attracted by their destinations, and repelled by obstacles and by each other. For more details on the simulation algorithms we refer to Köster et al. 2010. However, the discretization of the simulation environment will be described in detail since it is a crucial factor for the import of BIM data. Unlike other simulators (e.g. Helbing at al. 2009), obstacles do not necessarily block complete cells. Instead, thin walls will just cut the neighborhood between cells instead of occupying complete cells (cf. figure 3).

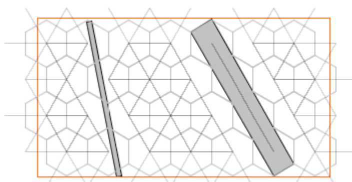

Figure 3: The (thinner) left wall does not occupy any cells, but cuts their neighborhoods (black connections)

This feature allows for a better compliance with the underlying structures, particularly regarding the simulation of narrow aisles, which might be important exit routes. In order to reflect the thickness of walls in the simulated behavior of persons, the repulsion value of the obstacle should be chosen accordingly.

Evacuation-specific extension of the BIM model

Since the structures required for pedestrian simulation (i.e. exit routes and accessible areas including stairs) are not natively supported by the IFC standard, we propose to extend the IFC standard by a number of entities as discussed below.

Accessible areas are usually part of the surface of a structural element – for example part of the upper face of a slab. In order to model accessible areas, we exploit the *IfcCovering* class. In order to establish a link between the structural element and an accessible area, we use the objectified relationship class *IfcRelCoversBldgElements* (cf. figure 4). Although an accessible area could be modeled as geometrical surface without an accommodating host, the association with a building element provides additional options.

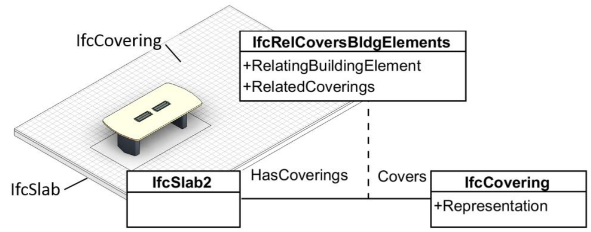

Figure 4: Relation between a building element (IfcSlab) and its accessible area (IfcCovering)

According to the BIM IFC standard, all physically existing objects like walls and slabs are subclasses of *IfcBuildingElement*. This IFC entity class can be used in combination with objectified relationships. Thus, the relationship defined above can be extended to arbitrary building elements.

An accessible area might be connected to other accessible areas forming compounds. Mutual accessibility is reflected by the IFC relation class *IfcRelConnectsElements* (c.f. figure 5). Each instance of an *IfcRelConnectsElement* links two *IfcCoverings* by a one-to-one relation. If one accessible area is connected to various others, each connection is implemented by a separate instance of *IfcRelConnectsElement*. If the geometry of the connection itself has to be stored in detail (for example a stair, which connects two levels of a building), this can be accomplished by employing a dedicated connection geometry. For this purpose, the *IfcRelConnectsElement* is equipped with an *IfcConnectionCurveGeometry* or an *IfcConnection-SurfaceGeometry*.

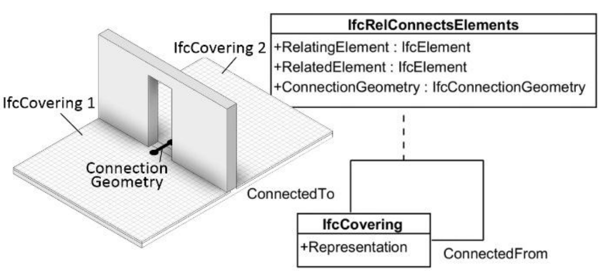

Figure 5: Connectivity of accessible areas represented by the IfcRelConnectsElements relation

The concept of a connecting geometry can also be used if the detailed modeling of the reality would be to complex. For examples, an elevator serving two levels can be excluded from the model. Instead, the connection between the involved *IfcCoverings* is shown by an *IfcEdgeCurve*. It is realized as a line starting at one covering, ending at another.

Since *IfcCovering* is a subclass of *IfcProduct*, a variety of geometric representations can be referenced (cf. figure 6), where line- and surface-based elements are most adequate. In our implementation we provide data-exchange interfaces for *IfcBoundedSurface* and *IfcFaceBasedSurfaceModel*.

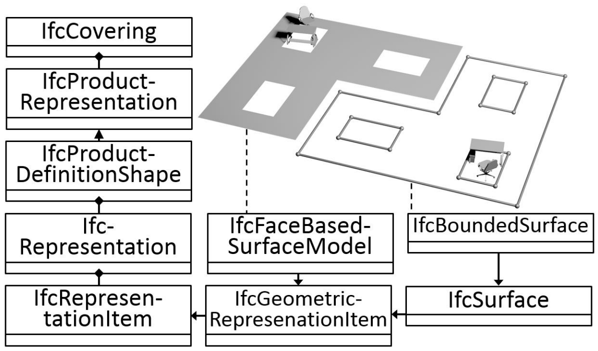

Figure 6: An instance of IfcCovering with one line-based and one surface-based geometric representation

Attributes - like the number of persons in a room - can be added to appropriate entities by the definition of user-specific property sets (*IfcPropertySets*). They allow for the definition of both numeric and textual attributes.

In the next section we describe how the concept can be implemented by means of a plug-in for Autodesk Revit 2013/2014. However, since IFC is an open standard, the implementation of the concept is not restricted to this specific application or vendor, but may be easily transferred to other products. The plug-in (developed by the *Technische Universität München*) is used to export the IFC model, which defines accessible areas as described above. The basic model comprising the accessible elements and their relations can be modeled in genuine Revit without any additional plug-ins. Since the internal data structures of Revit are not based on IFC classes, but on Revit families, the floor family *WalkableSurface* is exploited to replace *IfcCoverings* (cf. figure 7). Doing so, the full functionality of Revit can be used to model floor coverings. This particularly comprises snapping the floor coverings to other elements and to cut out inaccessible parts. In addition, connective geometries between areas can be defined by the Revit family *ModelLines*.

The model generated in Revit can be saved and distributed as a standard project file. If the Revit installation is extended by the evacuation-specific export plug-in, an IFC model instance can be generated incorporating the workable surfaces and their relations. In order to do so, the building is exported to the IFC standards. In addition, all elements of interest are processed and evacuation-specific information is added where necessary. For example all instances of the Revit family *WalkableSurface* are replaces by *IfcCoverings*.

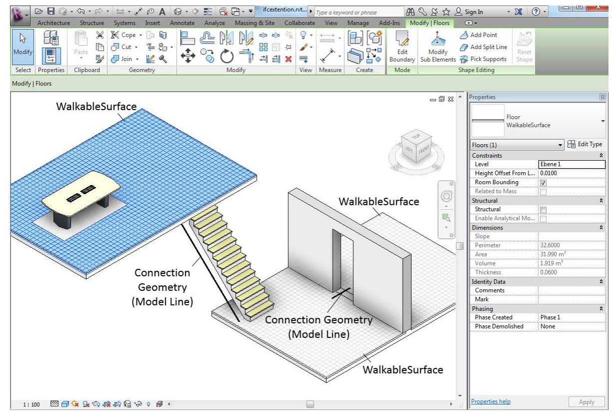

Figure 7: Modeling accessible areas in Autodesk Revit 2013/2014

Conversion into a pedestrian simulation model

Once the BIM model is generated, it can be imported into the pedestrian stream simulator. The import is currently implemented for IFC models generated by ArchiCAD and Revit.

Before the import of any structural elements, the level structure of the IFC model is evaluated in order to create the basic simulation model. The number of levels generated for simulation is not only influenced by the number of accessible floors, but also by the design of stair cases. For stairs with intermediate landings, the half-pace is modeled as a separate level (cf. figure 8).

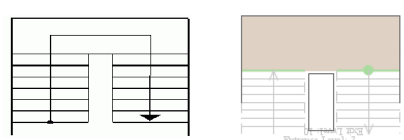

Figure 8: CAD model (left) and simulation model (right) of a stair with half-pace

Once the basic structure of the simulation model is generated, structural elements are added to guide the movement of the occupants. The list of the structural elements – which are imported into the simulation and used for interaction with the occupants – is currently restricted to walls, slabs, stairs, and furniture.

Walls

In a default multi-level scenario, the complete area of one level is accessible by pedestrians, but movements between levels are not possible. In order to restrict the movement within a floor, walls can be added to the scenario. This can either be done manually or the walls can be imported from the BIM model. As indicated above (figure 3), our simulator supports two different variants of modeling walls. Walls can either be represented as polygons (i.e. 2D objects) or polylines (1D objects). While the first version would enable a 1:1 import of IFC walls, it also induces some issues. Those are closely linked to the cellular discretization of our simulation environment.

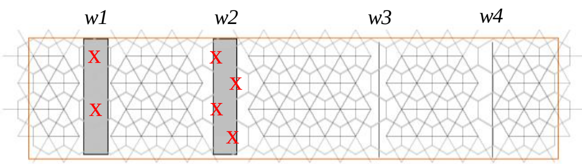

Figure 9: Different realization of walls, cells marked by an "x" are blocked

While wall *w1* blocks two cells in the grid, wall *w2* blocks four cells. Therefore, regarding 2D objects, the number of occupied cells is dependent on the location within the grid. In contrast, the solution based on 1D walls (w3 and w4 in figure 9) is independent of the location. Therefore, and because of the issues discussed in figure 3, we have chosen the latter variant for the BIM import. Unfortunately, the IFC standard does not support a unique mapping of 2D objects on 1D representation, since equivalent variations of certain wall structures are allowed. An important issue is the realization of edge connections. If the central line of a 2D wall is imported into the simulator to represent it as a 1D obstacle, different models of corners have to be taken into account (cf. figure 10).

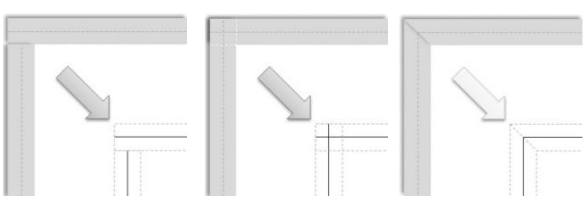

Figure 10: Variants of corners in BIM IFC

In order to cope with different variants of corners, we have introduced an additional post-processing step, which intersects consequent parts of the linear representation of a wall.

Slabs

As mentioned above, the complete area of a level is accessible, i.e. the simulator does not know from scratch what is inside and outside the building. Therefore slabs are imported in order to restrict the walking area. For example slabs are depicted in brown color in figure 2 (stair cases are not elements inside levels, but treated separately). If slabs contain holes, they cannot be imported directly into the simulator. Instead they are decomposed into triangles, which are the simple most polygons the simulator can handle. Simulation cells are generated in accessible (brown) areas only. Therefore, importing slabs is also a means of improving the performance of the simulation.

Stairs

Regarding the simulation, stairs are the most challenging objects to import from the IFC model. The reason is stairs having non-conform and non-hierarchical shapes, and IFC does not define compulsory elements, which are essential for the simulation model.

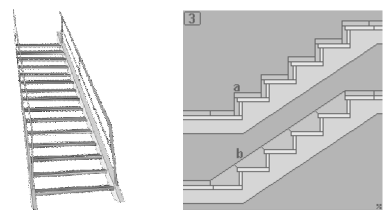

Figure 11: Typical shape of stairs (source: Wikipedia)

Current best practice for modeling stairs in BIM comprises the definition of a single 3D model with corresponding parameters (like tread depth and rise height). However, in order to identify the functional parts of a stair, a preprocessing step is still necessary. Regarding the simulation model, it is required to identify the connections of a stair to the floors at its beginning and at its end. Since handrails and fittings (cf. figure 11) are often modeled as one single entity without a dedicated IFC structure, these elements have to be identified geometrically. This is done by intersecting the stair model with the adjacent slabs and selecting the most distal intersection lines. In order to avoid this step, we have proposed additional options for connecting IFC elements. Half-paces are detected in a similar way and included as separate levels (see above).

Furniture

In the current version of the simulator, all furniture is treated as obstacles. We refrain from any details like persons climbing over tables or moving chairs etc. The IFC 3D objects representing the furniture are imported by a simple algorithm. Regarding only x/y coordinates, we subsequently add all points of the model to a polygon, which was initially empty. This excludes exotic objects featuring holes or bulges, which might be passed by persons.

Evacuation routes

If evacuation routes are defined, the import of slabs is omitted since evacuation routes are a stricter definition of walking areas. In this case, only cells included in evacuation routes will be generated by the simulator. This can be used for both optimizing evacuation routes and improving performance.

Simulation elements

Sources for the generation of pedestrians can either be defined manually or by extraction from the parameters of an *IfcCovering* (see above). The same applies to destinations and gathering points. The only thing left is to define the connection between sources and destinations. Currently this is simply applied by filling corresponding parameters of the *IfcCovering*, which was used as a source. The source contains a list of reachable destinations and the probability for a person to take one of the destinations (probabilities must sum up to 1.0). If there are different groups of occupants with different probabilities, an additional, overlapping *IfcCovering* with a corresponding destination list has to be defined for each group.

RESULTS

We have already tested the BIM IFC import of our simulator with publicly available examples. Figure 12 shows the import of the computer science department of the Karlsruhe Institute of Technology (KIT).

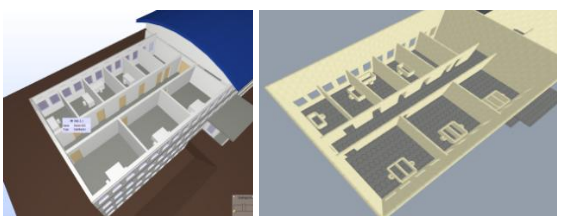

Figure 12: IFC model displayed by a BIM viewer (left) and the 3D view of the pedestrian simulation tool

The import was done from the plain IFC model without any modifications by the Revit plug-in. Therefore, only walls, slabs, stairs and furniture have been imported. Sources and destinations have been added manually. In that case (if no IFC containers are used), sources can encompass an arbitrary area within the accessible area. As one can see in the screenshot (figure 13), three areas have been added to generate persons. The simulator automatically omits obstacles when generating new persons in these areas.

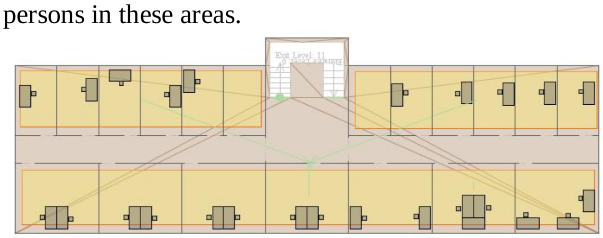

Figure 13: Add sources and destinations to model

The destination for these occupants was placed in the ground floor, which can be reached by the imported stairs. Now, the simulation model can be used to analyze different modifications of the building. As a toy example, we have chosen to provide a coffee bar in the center of the building. 90 occupants have been simulated to exit the floor containing the coffee bar. We varied the layout of the bar and compared the evacuation times with the original layout. In order to avoid random deviations, we used the mean value of 50 simulation runs for each scenario.

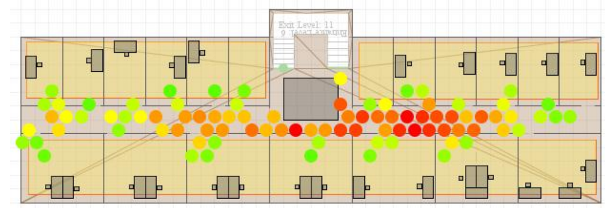

Figure 14: Modification with a coffee bar of 4x3m after 15 sec

As one can derive from figure 14, some issues regarding the modification can already be detected visually. In this case, a traffic jam forms in front of the bar, particularly in the right wing of the building (due to more persons occupying the right wing). A more detailed analysis can be done by looking at the table of results.

Table 1 Evaluation of modifications

SCENARIO	SIZE (BAR)	EGRESS TIME
A	*without*	183.4 sec
B	*2x2m*	183.1 sec
C	*2x3m*	182.7 sec
D	*4x2m*	189.4 sec
E	*4x3m*	196.2 sec

There is a significant influence on the evacuation time for the last two scenarios D and E compared to the original layout A (Δt: 6.0 sec and 12.8 sec, respectively). Therefore, the building manager would probably not choose one of those layouts. However, the slight differences in the evacuation times of the remaining scenarios B and C are due to statistical noise (≤ 1.0 sec), and therefore can be omitted.

The number of possible modifications is not restricted to a predefined list. Since the API of the simulator can be used to modify the building, automated changes (like shifting a wall) can be performed gradually.

DISCUSSION

The methodology proposed above enables a direct integration of BIM with a pedestrian stream simulation. This supports the assessment of various safety aspects of a building like evacuation planning and avoiding high pedestrian traffic. However, the validity of the results is limited by some human factors. Since each of the occupants acts independently and individually, the worst case evacuation time cannot be anticipated by a simulation. For example, delays due to injuries or uncommon ways out of the building (e.g. if somebody returns to pick up items left behind) are not taken into account. Therefore, the calculated evacuation times have to be regarded as best case scenarios, where each of the occupants knows the optimal egress route out of the building and follows that route without disturbances. Nonetheless, assessing the evacuation time under these assumptions still makes sense. It can reveal conceptual design errors of the building, which prevents a proper evacuation even under optimal circumstances. The same kind of evaluation has to be shown if a new passenger aircraft is ready for admittance. The regulations for FAA admittance of an airplane require an evacuation time below 90 seconds in dark conditions and only half of the exits may be used (U.S. Congress Office of Technology Assessment. 1993). However, this can only be seen as a benchmark. Under real circumstances, i.e. in case of an emergency on an aircraft, it might take significantly longer to evacuate the plane – if possible at all. The same applies to the evacuation simulation of buildings. The values should be regarded as an important benchmark, having in mind the limitations when preparing for real evacuation scenarios.

Due to the reasons introduced above, the simulation algorithms are focused on best case scenarios and take into account physiological aspects like velocity distributions and uniform interactions, rather than psychological aspects like stress or uncommon behavior. The physiological aspects of a pedestrian evacuation are well documented and lots of test cases are available. We designed the simulator to comply with the evacuation guidelines for passenger ship evacuation, which were later adopted by the guidelines for civil engineering (IMO Guidelines. 2002; RiMEA Guidelines. 2009). Figure 15 shows a test from the catalogue, where the flux of the pedestrians is measured for different densities.

As shown in figure 15 (left side) an annular corridor is generated and more and more persons are injected to circle around. The injection stops after the maximum density has been reached (Weidmann: 5.4 persons/m²).

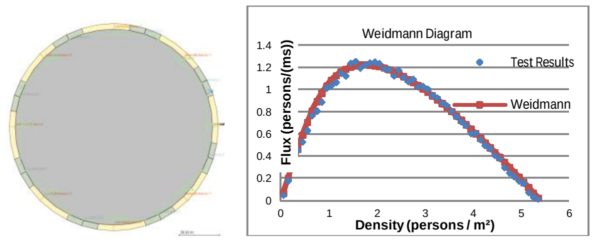

Figure 15: RiMEA Test 4; flux/density relation

The right side of figure 15 shows the test results for each density after calibration. Apart from these official tests, we also generated our own test scenarios. We have measured the evacuation time during the evacuation drill in a public school (Mayer et al. 2011). In addition, we assessed some features like the up- and down-stair velocities with a group of police students (Hartmann et al. 2011).

CONCLUSION

Today many issues regarding the safety and comfort of occupants in buildings can be addressed by a pedestrian simulation. Starting in the planning stage of the building, simulations can help to assess evacuation times and to optimize certain structures like stairs cases or floor planning. During operation of the building a pedestrian simulation can be embedded into the building management system in order to calculate individual exit routes just in time regarding the current situation. For example, if a fire is detected in the ground floor near a stair case, occupants on all floors can directly be routed to an alternative exit (cf. figure 16).

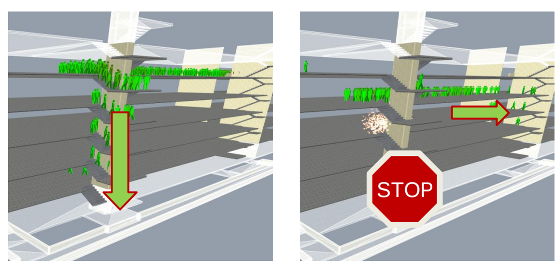

Figure 16: After the detection of a fire, the simulator calculates new individual egress routes

The new exit route can be communicated via loud speakers or published individually via mobile devices.

Currently, the simulator is still executed separately, after the BIM model has been adjusted by the CAD application plug-in. However, in near future the simulator itself will become an integral part of the plug-in in order to enable a seamless integration between building design and simulation. After implementing these further steps, it will also be possible to give a direct feedback from the simulation into the BIM model. Certain structures like an exit door could be directly adjusted by the plug-in in the CAD application, based on the simulation results (e.g. the width of an exit door). In the medium term it is expected that BIM as well as pedestrian simulations will play a growing role in official building codes.

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