Multilevel Analysis of Fire Escape Routes in a Virtual Environment

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The paper discusses the computer-aided analysis and evaluation of fire safety in relation to pedestrian circulation in buildings, i.e., fire escape routes. It describes an approach employing both detailed and abstract representations. The goals of the research include: (a) the development of a pyramidal structure that links design analyses at different levels of abstraction.; (b) *the evaluation of abstract, normative levels of the analysis (and though these of underlying legal and professional principles) using the results* of *detailed, accurate simulations; and (c) the development a reliable framework for testing human behaviour in fire hazard.*

Keywords:fire safety, escape routes, analysis and evaluation, recognition, simulation

1 Computer-aided analysis and evaluation

Computer-aided analysis and evaluation are among the major promises of computerization in architectural design. The architect should be able to predict and evaluate the behaviour and performance of a building at any stage of the design process. Feedback from such evaluations is instrumental for the evolution and improvement of a design, as well as for presenting and arguing for a specific solution. Computerization of analysis and evaluation is seen as a qualitative and quantitative improvement over conventional methods and techniques. The computer can perform analyses automatically, thoroughly and connect analyses with the geometric representations of computer-aided design.

Analysis of architectural designs takes place at two basic levels:

(a) An abstract normative level governed by rules of thumb and global constraints. At this level one finds the most legal norms and requirements. These form a distillation and crystallization of professional and general knowledge on the built environment.

(b) The more precise and detailed level of simulation of the projected form and behaviour of the building under design.

Early CAAD research was concerned more with the first level. Reasons this can be ascribed to include compliance with established architectural and engineering practices, limitations in computational power and simplistic theoretical and computational models. Recently CAAD has been more attentive to the possibilities of realistic simulations for the design and analysis of the built environment. One of the reasons has been the growing availability of suitable theoretical and computational models [1] . Another reason is the realization that direct manipulation of detailed design models in a virtual environment comes closer to similar real-world experiences than abstract representations do [2, 3] - a realization that relates to direct perception [4-6]

While we have good reasons for assuming that realistically and accurately detailed design representations in an interactive environment, as in virtual reality, enhance the designers' understanding of their designs and of the potential behaviour of future buildings, we should also consider our perceptual and cognitive limitations (for example, limitations of working memory and of visual acuity). Such limitations suggest that abstract representations might have a place in the designing and overall manipulation of the built environment [7,8] The paper describes an approach to computer-aided design analysis and evaluation employing both detailed and abstract representations, as implemented for fire safety in relation to pedestrian circulation in buildings, i.e., fire escape routes. Central to our approach is a pyramidal structure that accommodates analyses at a variety of specificity levels an c[facilitates correlation of results and underlying principles.

2 Fire safety and pedestrian circulation

Fire safety is one of the oldest problems in the built environment. Improvements in building materials, ignition prevention and fire extinguishment have reduced the extent and frequency of fires in buildings. Still, even a minor fire poses a serious threat to the life a building's occupants. The main reason is that fire and smoke cannot be easily constrained by architectural fire fighting means. For example, diluting smoke so as to keep a space habitable is practically impossible [9] . Evacuating all occupants as soon as fire is detected in the building still remains the safest option. Escape links fire safety with circulation. Our analysis of pedestrian circulation in buildings is based on the principles of the dual graph representation [10] and in particular to the correlation of activity patterns with the spatial articulation of a building. Interestingly, fire safety engineering makes use of similar representations. Escape analysis graphs are used to determine the succession of spaces in a route. The topologic pattern of the route is then correlated with the geometry of the building in order to assess the exact shape and length of the route [11-13] In determining the form of a circulation pattern, the goals of the movement are of obvious importance. For fire escape the goals are defined by the escape strategy. In fire safety engineering one distinguishes between three general escape strategies [9]:

(1) Direct escape from the burning building to a safe place on the ground (egress).

(2) Escape to a place of safety in the same building (refuge). This strategy is mostly used for people with reduced mobility and in large, complex buildings.

(3) Rescue by persons from outside the building, e.g. by means of ladders. This strategy is normally a last resort to be used when the previous two have been made impossible by the fire.

In the present paper we are primarily concerned with the first strategy (egress) which offers the highest degree of safety. Moreover, the second strategy (refuge) can be associated with the first stage(s) of egress.

3 A multilevel approach to the recognition and analysis of escape routes

3.1 Abstraction and specificity

Design analysis and evaluation take place at a variety of specificity levels. For example, in the early phases of the design process abstract or general rules derived from professional experience, the brief or legal requirements are applied as basic arguments for or against a particular type of design solution. These rules are often integrated in the generative process by which a designer arrives at a solution. When designing a residential area, for instance, one could include a bias towards a specific orientation that offers better daylighting.

Other analyses rely on more developed systems which accommodate concrete rules and principles. These typically relate to specific design aspects or subsystems of a building. Such rule systems are applied in various analytical forms, including diagrams (as in daylighting and heating), and require more and more specific Information than what a building type or a sketch signifies.

Even more detailed analyses are based on simulations of the projected behaviour of the building. These require precise information on several aspects of a building and on its surrounding environment at a high level of specificity. For example, air flow in a building depends on factors such as the orientation and form of the building, the position, shape and dimensions of openings, the form and size of spaces, the activities that take place in the spaces, as well as on climatic factors at the location of the building. Despite algorithmic and computational difficulties such simulations have been recently attracting attention under the influence of rapidly developing area, such as chaos theory and scientific visualization. It is noteworthy that, contrary to popular belief, the different analysis levels do not form a clear progression from abstract to specific, nor follow a schematic sequence of design phases -again from abstract to specific. Abstract rules may be applied to detailed designs and intricate simulations may precede the selection or elaboration of a central design idea. The level of the analysis is usually chosen in an opportunistic manner, depending on the scale or nature of the design project. Moreover, the choice is often imposed by other parties, such as the clients, the authorities or cooperating engineers. An important aspect of the distinction between different analysis levels is quantification. Normative analyses and principle or rule based systems generally appear as returning measurable results. This is partly due to that these analyses are performed within closed systems with a clearly defined scope and goals. Regardless of inherent limitations, it is undeniable that such analyses are useful for evaluating the compliance of a design to legal requirements and to general design principles. The question is whether the results of the analyses are sufficient for accurately predicting the behaviour and performance of a complex object such as the average building. Simulations - in particular those carried out in the framework of scientific visualization link measurement to visual representation. This link also brings together intuitive judgements (on the basis of the visualization) and precise, quantitative models that predict the behaviour and performance of a building. The possibilities of this conjunction are considerable. There is, however, an inherent danger that deserves particular attention. The familiarity and apparent effortlessness of intuitive assessment on the basis of realistic representations may transform the evaluation process into an endless trial-and-error parade of alternatives and variations. The rules and principles of the normative level can offer valuable guidance in this respect.

3.2 Multilevel structures

Multilevel structures have been successfully employed in other computational applications involving both abstraction and precision. In computer vision and image processing multiscale pyramidal representations link different levels of abstraction and facilitate use of the results of one level for guiding and controlling the operations at another level. For example, an image is analysed at a variety of resolution levels. At the lower resolutions the global structure of the image is recognized, e.g. the overall segmentation of the scene into regions tentatively corresponding to objects. This structure is used as a guideline for the analysis of the image at higher resolutions. There object recognition takes place primarily within the regions proposed as segments [14-16].

For the analysis and evaluation of aspects such as pedestrian circulation and fire safety a multilevel structure presents similar possibilities. On abstract, normative levels a design is analysed using general criteria. Such criteria apply to designs in the early stages, as well as finished designs. For example, the number and length of escape routes in a building refers to information readily available practically at all stages of the design process. The results of the analysis offer guidance for the further development of the design and as starting points for analysis in more detail. The evaluation of the number and length of escape routes in a preliminary design gives rise to questions that have to be resolved in the course of its further development into a precise specification of the built environment. In a complete, detailed design the same evaluation represents a global assessment that identifies local problems and negative factors. By concentrating analysis on the corresponding areas and aspects it is possible to improve the design by means of local or partial changes

Multilevel analysis assists in making explicit and clarifying the principles behind legal and professional norms, rules and requirements. Rather than merely enforcing norms and rules and satisficing requirements, a designer has to comprehend why and how acceptable results are to be achieved and creatively integrate such knowledge in the designing of the built environment. Questioning the established norms and testing stereotypical solutions form part of the same process. Any practising architect can provide evidence on how outdated or inadequate existing norms and regulations can be and on how frustrating this can be for the development of innovative solutions. In our research we are using a multilevel pyramidal structure to link the following levels of analysis and evaluation:

(a) The low, normative level that offers automated recognition and calculation of the shortest escape route for each space in a building according to the current Dutch regulations. This level is based on a general model for the recognition of pedestrian circulation routes in buildings [17]

(b) The intermediate level where autonomous virtual robots navigate in the virtual building on the basis of user-input principles. The purpose of this level is to test assumptions that underlie the normative thinking of the low level. By simulating a behaviour explicitly governed by the corresponding principles it is possible to evaluate the sufficiency of the principles and explore alternatives and relationships between principles.

(c) The high level where virtual reality systems are used to monitor and register the behaviour of test persons. Their reactions are recorded, analysed against the results of the previous two levels and re-used in a generalized form as profiles of virtual autonomous persons. These act as a more elaborate and realistic version of the virtual robots used at the intermediate level. Each level is in principle self-sufficient. It represents a different level of specificity and employs a corresponding approach to the recognition and analysis of fire escape routes. In a pyramidal system self-sufficiency is sacrificed for the sake of coordination. Each level investigates fire escape within the constraints defined by the results of the immediately lower level (in terms of specificity). The intermediate level, for instance, uses virtual robots for testing the assumptions behind the normative level. Rather than letting the virtual robots loose in the virtual building, we restrict their field of action to the spaces traversed by the routes recognized at the normative level. The aim of the intermediate level is not to refute or contradict the proposed routes but to refine their form by adding tolerances and taking into account factors that were left out at the normative levels.

4 The normative level: rules and regulations

4.1 Requirements

While legal fire escape requirements and professional norms are qualitatively well-defined, their quantitative evaluation in designs and buildings remains unresolved. Quantitative models for the evaluation of fire escape as a whole or of particular aspects of escape, such as evacuation time and exit width [12, 13] , are often disconnected from the tangible global or local problems that trouble architects, authorities and fire safety engineers. As a result, evaluation of escape routes in an architectural design is usually based on empirical analyses. These project fire and evacuation patterns and evaluate the adequacy of escape facilities in relation to the appropriate building regulations.

The relevant Dutch building regulations (as they apply to housing) can be summarized as follows [18]

(1) The length of a fire escape route is calculated on the basis of the shortest route. This is the direct distance between two points of exit or between the point of exit from a space and the farthest point in the space (measured over movable obstacles such as furniture). The minimal distance of the shortest route from building elements is thirty centimetres. Figure 1 depicts the shortest escape route in an L-shaped space. On stairs the shortest route is measured on the ascent line.

(2) A building is subdivided into fire compartments and subcompartments. A compartment should correspond to a functional unit, e.g. a dwelling, and be no larger than five hundred square metres. Compartments are separated by fire-resistant walls and floors so as to ensure fire containment. Subcompartments are groups of spaces with a floor area up to forty square metres. A space larger than forty square metres also qualifies as a subcompartment. A subcompartment should be able to contain fire for a limited period of tine.

(3) Each (sub)compartment should have at least two exits leading to two independent escape routes, so that all occupants can escape without congestion and regardless of the way the fire spreads. However, it is acceptable that the two routes have a common part within the (sub)compartment.

(4) Escape is subdivided into stages. The first stage is escape from the initial (sub)compartment where the occupants happen to be when evacuation starts to a protected circulation space. If the initial space is a large communal space the length of the shortest route in this space should be no longer than twenty metres. The maximal length of the shortest route in the (sub)compartment is thirty metres.

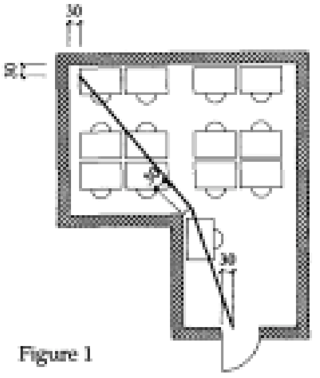

Figure 1

(5) The second stage is escape to a safe place on the ground, often through protected staircases and possibly through (temporarily) safe compartments. The length of a horizontal route within a compartment should be no longer than thirty metres. Communal spaces on a floor level higher than thirteen metres above ground (or five metres for large housing complexes) should have at least one escape route through a protected staircase that gives directly to the ground.

4.2 Recognition of escape routes

To ensure objectiveness the escape routes of a building are recognized automatically, on the basis of computer drawings where the relevant entities, i.e., the spaces and access between spaces are explicitly represented. Computer drawings that do not include such information and analog drawings require a preprocessing stage where spaces and building elements are recognized [19-22] The geometric description of the building is transformed into a topologic representation (access graph). In the topologic representation each space in the building forms a node. A link between two nodes represents a door or similar opening.

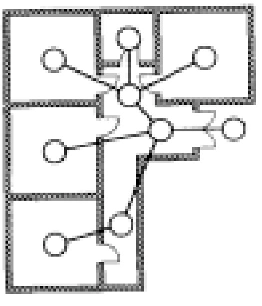

Figure 2

Figure 2 shows a topologic representation superimposed on the floor plan of a school building in The Netherlands. Recognition of the escape routes begins with the topologic representation. The possible escape routes from each use space are recognized on the basis of an initial exhaustive enumeration of all escape possibilities. Each link between the node of the space and adjacent spaces is treated as a starting point for an escape route. A link may be traversed only once by the same route. The process ends when every route meets a circulation space or a dead end in a use space. Routes leading to dead ends are rejected. When two routes end at the same pair of nodes, the longest route is rejected. The remaining subgraphs represent the topology of the escape routes in the initial (sub)compartment.

Figure 3 shows the subgraphs of escape routes in a subcompartment.The next stage in the recognition process is the transformation of the recognized escape routes into geometric patterns. For this we require (a) a starting point for each route and (b) correlation of links with doors or similar openings. The starting point is determined in accordance with the Dutch building regulations. In spaces with only one exit it is the farthest point from the exit, normally a point near a corner of the space diagonally opposite to the exit.

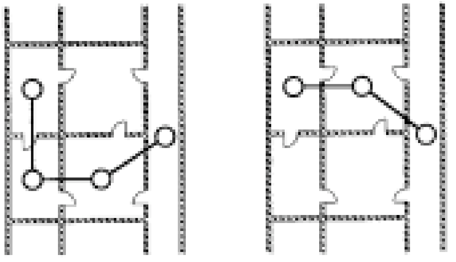

Figure 3

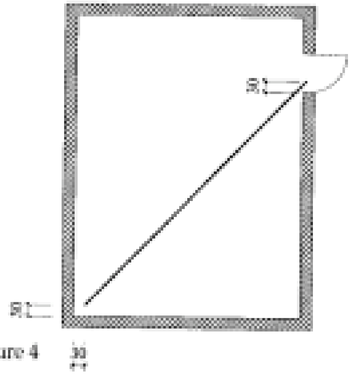

Figure 4

Figure 4 depicts the route in such a space. Note that both the farthest point and the route endpoint by the exit observe a distance of thirty centimetres from building elements. In spaces with two or more exits the space is first subdivided into parts corresponding to the escape field of each exits. Each part is then treated as a space with only one exit. Figure 5 depicts the subdivision of a space with two exits.

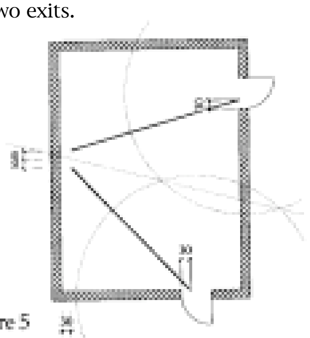

Figure 5

Once the starting point has been identified the geometry of the route can be defined as the sequence of straight line segments linking the starting point and the doors corresponding to links in the subgraph, in the same order as in the subgraph. The correlation of links in the subgraph of a route with doors in the floor plan is straightforward, as the doors have already been identified and used for the recognition of the links. A line segment in the route that intersects walls of the building is replaced by two other segments using a point thirty centimetres off the common corner of the walls as an additional vertex between the two vertices of the original segment. Figure 6 shows the routes corresponding to the subgraphs of Figure 3.

The last stage in the recognition of the escape routes concerns the second stage of escape, the route that links the exit of the (sub)compartment with the ground outside the building. This is recognized in the same way as the route within the (sub)compartment. An exhaustive enumeration of alternative routes in the topologic representation is followed by a selection of acceptable subgraphs. Finally the subgraphs are transformed into geometric patterns by linking the corresponding doors in the proper sequence. Figures 7 and 8 depict topologic and geometric representations of escape routes in the building of Figure 2.

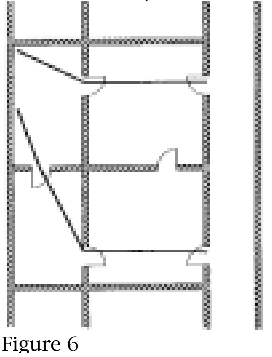

Figure 6

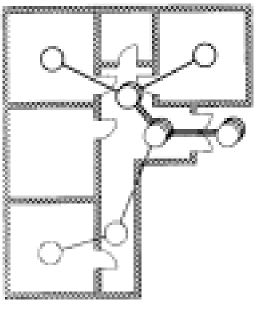

Figure 7

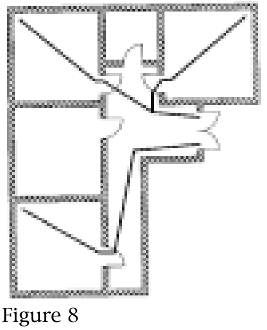

Figure 8

The end product of the normative level is a number of escape routes that are formed by linking routes within the initial (sub)compartment and routes between the (sub)compartment and the ground outside the building. As the number of possible routes and the length of each route are known, analysis at this level is deemed sufficient for evaluating escape against the fire safety requirements of the Dutch building regulations. The escape routes recognized at the normative level can be used for the analysis of dynamic aspects of fire escape. The length of a route and the presence of alternative routes are critical but consideration of each route or (sub)compartment in isolation ignores the complexity of the evacuation process. This can be studied only on the basis of all routes and all escape flows. Intersecting or converging routes increase the number of problems of evacuation and ask for careful planning and phasing of the evacuation. This relates to the speed of movement along the escape routes and to the speed and direction of fire spread in the building. Dynamic representation of movement along the recognized escape routes can be used to study different evacuation scenaria.

S The intermediate level: artificial users

Normative analyses are based on compact, abstract systems of rules and principles which allow for a relatively fast assessment of success or failure. While one should accept that these rules and principles represent an obvious starting point for the analysis, it would be unwise to accept the completeness and infallibility implied in textbooks and legal guidelines. On the contrary, a major task of the designer is to question the underlying assumptions, especially when dealing with extreme conditions. The underlying assumptions concerning human behaviour in the analysis of fire escape make good common sense.

When one is confronted with fire hazard, the shortest route out of the building is the obvious choice. Moving alongside walls at a distance closer than thirty centimetres is impractical. Nevertheless, it is a fact that humans do not fare as well in fire situations. Panic is indeed less common than one might fear but, despite all warnings, quite a few occupants attempt to escape by means of lifts. Moreover, choice of route is heavily influenced by familiarity. Rather than opting for the shortest route, one tends to follow the route used under normal circumstances.

The precise and accurate simulation of human behaviour in the built environment is clearly beyond the scope of our research. What we are attempting is an investigation and refinement of the principles underlying normative fire escape analysis and evaluation, towards the development of an environment where the resulting expectations can be matched against certain reactions of test persons. The first of these aims is explored at the intermediate level of our system where artificial users verify and elaborate the escape routes recognized at the normative level. The intermediate level relates to knowledge based analyses of fire escape [23, 33]. The main difference lies in that the intermediate level does not aim at a realistic simulation but at experimentation that may enrich the normative level. Our artificial users are simple virtual robots that move in virtual buildings on the basis of small sets of rules. These rules relate to the principles underlying the analysis at the normative level. Some of the most important are

(a) the use of direct distance for the measurement of the escape route,
(b) the distance of thirty centimetres from building elements and
(c) the speed implied by the maxima for escape route length.

The virtual robots are used to test alternatives and variations of these principles, such as partial or total avoidance of movable obstacles. This allows us to investigate differences in length between direct distance and variations of the travel distance measurement.

The wanderings of the virtual robots are constrained by the escape routes that have been recognized at the normative level. A virtual robot is allowed to move in the sequence of spaces traversed by a route. As a result, the paths of the robots form mostly variations around the shortest routes. As expected, they all converge to the exits of the spaces but within the space they follow different trajectories. The picture formed by the different paths is strongly reminiscent of observed movement patterns on stairs [24]: while movement is rather dispersed around the planned ascent line, there is an undeniable consistency in the patterns that can be reduced to a relatively small number of principles and tolerances around canonical values. Quantification of these principles and tolerances remains a problem that may be resolved by the introduction of chaotic principles. These are probably better suited for the treatment of the complexity and unpredictability in the accumulation of paths traversed by virtual robots, e.g. through the identification of a pattern of attractors [25].

Tolerances around the shortest route can be of significance for the speed of escape. Maximal lengths in current legislation and professional recommendations are usually based on the distance that an able-bodied person can walk in one to three minutes (times vary). However, experience in the evacuation of mothers with children, the elderly or the handicapped teaches that different types of occupants require different treatment. The results returned by virtual robots governed by different principles could indicate the size of tolerance that might be required for making suitable affordances in escape route design.

Perhaps more important than the evaluation of principles governing the normative level is the application of the virtual robots in the study of these and similar principles under more realistic conditions. At the normative level the escape route is an abstract entity with topologic properties and a certain length but little or no interaction with other occupants or with the precise form of the building. At the intermediate level we are using virtual robots to elaborate on the escape routes under extreme, crowded conditions. Using minimal kinetic information and escape principles from the normative or the intermediate level, we are developing virtual robots that simulate human movement during escape from a cinema (Figure 9). The purpose of the simulation is not a realistic reproduction of human movement but an investigation of temporal and geometric aspects of the escape route. The average and maximal time required for a virtual robot to leave a seat, sidestep out of a row to the corridor and from there walk to the exit of the cinema serves as a useful comparison with the normative shortest route for the same space. Moreover, interaction between virtual robots in the simulation provides a more realistic picture of possible conflicts and congestion. A cinema is a suitable choice for the investigation of such interaction, as escape from a cinema is characterized by high density and a simultaneous surge from all over a large space towards a small number of exits.

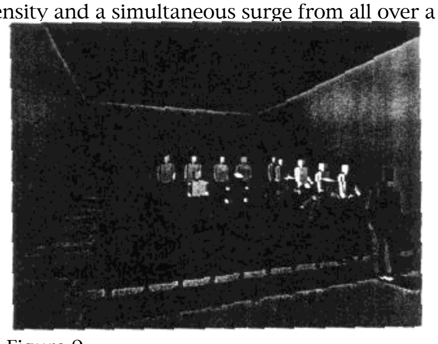

Figure 9

6 The high level: registration and simulation

Detailed simulation and prediction of a building's fire behaviour is necessary because of the dynamic and chaotic nature of the problem. Fire development and spread depends on a number of variable conditions and ad hoc situations, such as the nature, amount, density and distribution of flammable material, the proximity of such material to the walls and the ceiling, the size and especially the height of a space, the size and shape of windows. These factors and their interrelationships are not amenable to simple rule systems. In recent years developments in computer graphics and scientific visualization have led to rapid growth in the applications of techniques such as interactive computational fluid dynamics to predict fire spread and smoke movement in buildings [26-30].

Movement in a smoke-filled room poses physical and psychological problems that are not as easy to simulate as fire and smoke. Computer simulation of human behaviour remains a formidable task, especially in architectural and engineering applications where autonomy and interaction with the virtual context are of paramount importance [31,32]. It is therefore not surprising that when human presence is required in a fire simulation, the human figures are often simply superimposed on the images of the fire.

In our research we are adopting a different approach. Instead of attempting to reproduce human behaviour in a fire simulation, we are using fire simulation in a virtual reality system as the context of human interaction. Test persons immersed in the virtual reality system are confronted with the simulation of fire in a building. The escape routes recognized at the normative level and elaborated at the intermediate level can be indicated in the simulation, for instance by escape lighting. The response of the test persons to the stimuli they receive can be used to evaluate aspects of fire safety, such as familiarity with the escape routes and visibility of exits in a smoke-filled space. Aspects such as the length and shape of the route or escape speed are more dependent on the possibilities and quality of the immersion equipment.

Fire simulation at the high level of our system aims at more than a virtual fire drill that can be used to evaluate escape routes interactively. Immersion equipment can be used not only to convey stimuli to the test persons but also to register their responses to information they receive from the simulation. The responses can be used to compile profiles of virtual occupants. These are governed not by simple rules and principles, as the virtual robots of the intermediate level, but refer to actual cases encountered by the test persons.

Our ultimate goal for the higher level is the development of virtual autonomous persons who can be integrated in the fire simulation so as to play the role of the occupants. By multiplying the profiles derived from test persons it is possible to generate large numbers of virtual occupants who exhibit different behavioural patterns and, therefore, can be used in realistic escape simulations. Interaction between virtual occupants and between virtual occupants and the simulation of the burning building is an essential prerequisite to the development of autonomy is the system. A simulation of truly autonomous virtual occupants escaping through the routes recognized and elaborated at the normative and intermediate level forms an advanced interactive environment where relationships between escape and other aspects of fire safety, such as extinguishment and containment, can be studied and evaluated in detail.

7 Future developments

So far we have been concentrating our efforts on the basis of the whole system, the normative level. We are currently testing this level with extreme cases so as to identify possible exceptions and refine accordingly our algorithms. The intermediate level is also under development, with several virtual robots using simple navigation strategies. The main problem we are facing at the intermediate level is constraining the navigation strategies to a manageable number of meaningful scenaria. With regard to the higher level we are in the process of selecting the fire simulation that will provide the context of our analyses. Interactive manipulation is one of the primary criteria for the selection. In this respect we are limited by the possibilities of immersion systems Completion of all levels would mean that the initial version of the system is fully implemented. This, however, is but an operational goal. Parallel to the implementation of the three analysis levels as outlined above, we intend to enrich the scope of the system gown by taking into account aspects and factors that have been left out in order to scale down the problem, such as the volume of an escape flow and the relation between flow volume, speed and breadth of the escape route. Other aspects that can be improved concern elements of the computational structure of the pyramid, such as feedback.

Another issue that is not been considered in the initial version of the system is the stages of fire following ignition. This is something we intend to integrate in the dynamic simulation at a later stage when we extend the forms of interaction between occupants and the building. This means that for the moment we do not attempt to address phenomena such as backdraught, i.e., the eruption of flames from a smouldering fire when mixed with a fresh supply of oxygen, e.g. by a door being opened in the process of escape or fire fighting.

8 Bibliography

[1] Maver, T., Software Tools for the Technical Evaluation of Design Alternatives., in CAAD Futures '87, T. Maver & H. Wagter, (eds), Amsterdam: Elsevier, 1987.

[2] Schmitt, G., Architectura et Machina, Wiesbaden: Vieweg, 1993.

[3] Schmitt, G. N., Architectura cum machina, in Visual Databases In Architecture: Recent Advances In Design And Decision Making, A. Koutamanis, H. Timmermans, & I. Vermeulen, (eds)., Aldershot: Avebury, 1995.

[4] Gibson, J. J., The Perception Of The Visual World, Boston, Massachusetts: Houghton Mifflin, 1950.

[5] Gibson, J. J., The Senses Considered as Perceptual Systems, London: George Allen & Unwin 1966.

[6] Gibson, J. J., The Ecological Approach to Visual Perception, Boston, Massachusetts: Houghton Mifflin, 1979.

[7] Schmitt, G., Expert Systems In Design Abstraction And Evaluation, in Computability of design, Y. E. Kalay, (ed), New York: Wiley, 1987.

[8] Koutamanis, A., Preliminary Notes on Abstraction., in Advanced technologies. Architecture, Planning, Civil Engineering, M.R. Beheshti & K. Zreik, eds., Amsterdam: Elsevier, 1993.

[9] Stollard, P. & J. Abrahams, Fire from First Principles, 2nd ed., London: E. & F. Spon, 1995.

[10] Steadman, J. P., Architectural Morphology, London: Pion, 1983.

[11] Berlin, G. W., The Use of Directed Escape Routes for Assessing Escape Potential, Fire Technology, 14(2), 1978; p. 126-135.

[12] Marchant, E. W., Modelling Fire Safety and Risk, in Fires and Human Behaviour, D. Canter, ed., Chichester: Wiley, 1980.

[13] Shields, T. J. & G. W. H. Silcock, Buildings and Fire, Harlow, Essex: Longman, 1987.

[14] Marr, D., Computer vision, San Francisco: W.H. Freeman, 1982.

[15] Rosenfeld, A., (ed), Multiresolution image processing and analysis, Berlin: Springer, 1984.

[16] Rosenfeld, A., Pyramid Algorithms for Efficient Vision, in Vision: Coding and Efficiency, C. Blakemore, ed., Cambridge: Cambridge University Press, 1990.

[17] Koutamanis, A. & V. Mitossi, On the Representation of Dynamic Aspects of Architectural Design in Machine Environment, in Advanced Technologies. Architecture, Planning, Civil Engineering, R. Beheshti & K. Zreik, eds., Amsterdam: Elsevier, 1993.

[18] Ministerie van VROM, Brandveiligheid woningen en woongebouwen, Den Haag: 1992.

[19] Koutamanis, A. & V. Mitossi, Computer Vision in Architectural Design, Design Studies, 14(1), 1993; p. 40-57.

[20] Koutamanis, A. & V. Mitossi, Architectural Computer Vision: Automated Recognition of Architectural Drawings, in Design and Decision Support Systems in architecture. H. Timmermans, ed., Dordrecht: Kluwer, 1993.

[21] Koutamanis, A. & V. Mitossi, Adding Visual Recognition to the Capabilities of Computer-Aided Design. in Visualization and Intelligent Design in Engineering and Architecture, J.J. Connor, et al., (eds), London /Southampton: Elsevier/Computational Mechanics Publications, 1993.

[22] Koutamanis, A., Recognition and Retrieval in Visual Architecural Databases, in Visual Databases in Architecture. Recent Advances in Design and Decision mMaking., A. Koutamanis, H. Timmermans, & I. Vermeulen, eds., Aldershot: Avebury, 1995.

[23] Ozel, F., An Intelligent Simulation Approach in Simulating Dynamic Processes in Architectural Environments, in CAAD Futures '91, G. N. Schmitt, (ed), Wiesbaden: Vieweg, 1992.

[24] Templer, J., The Staircase: Studies of Hazards, Falls, and Safer Design, Cambridge, Massachusetts: MIT Press, 1992.

[25] Field, M. & M. Golubitsky, Symmetry in Chaos. A Search for Pattern in Mathematics, Art And Nature, Oxford: Oxford University Press, 1992.

[26] Cox, G., et a!., Fire Simulation in the Design Evaluation Process: An Exemplification of the Use of a Computer Field Model. in Proceedings 5th International Interfiam Conference, London: Interscience, 1990.

[27] Brodlie, K.W., et al., eds., Scientific Visualization -Techniques And Applications, Berlin, Springer-Verlag, 1991.

[28] Jones, P.J. & G.E. Whittle, Computational Fluid Dynamics For Building Air Flow Prediction -Current Status and Capabilities, Building and Environment, 27(3), 19921- p. 321-338.

[29] Whittle, G.E., Ong, I. B. S. & Gardiner, A. J., Prediction of Wind Driven Ventilation, Fire and Smoke Movement on Offshore Production Platforms using CFD, in Proceedings Conference on Engineering Applications of Computational Fluid Dynamics, London: Institute of Mechanical Engineering, 1993.

[30] Cox, G., Compartment Fire Modelling, in Combustion Fundamentals of Fire, G. Cox, (ed), London: Academic Press, 1995.

[31] Steinfeld, E., Toward Artificial Users, in Evaluating and Predicting Design Performance., YE. Kalay, (ed), New York: Wiley, 1992.

[32] Thalman, N.M., Virtual Humans Acting in Virtual Reality, in Visualization and Intelligent Design in Engineering And Architecture. J. J. Connor, et a!., eds., London /Southampton: Elsevier/Computational Mechanics Publications, 1993.

[33] Stahl, F. I., B Fires-11. A Behaviour-Based Computer Simulation of Emergency Egress During Fires, Fire Technology, February, l982;pp. 38-48.

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