TOWARDS A DIGITAL REPRESENTATION OF PHYSICAL PHENOMENA TO ASSESS COMFORT IN FUTURE ENVIRONMENTS

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ABSTRACT

This paper presents the concept and a test implementation of a digital representation of the physical world designed to assess comfort quality in future environments. An integrated set of physical phenomena is modeled three-dimensionally to investigate the dynamic behavior of design objects holistically.

The formulation supports the integration of computational simulation in the performance-based design process. It employs the principles of geometrical and physical selfcontainedness to avoid that complex geometrical and physical circumstances have to be specified at design time. The concepts of congeneric cells and congeneric conjunctions are introduced to simulate various physical phenomena simultaneously with a uniformly structured set of equations.

The concept, the prototype implementation and selected test cases are presented. Although it was not possible to implement all features and model parts completely, the research and the discussion of its achievements make valuable contributions towards more effective integration of computational simulation in the performance-based design process.

KEYWORDS

digital design, performance-based design, integration, comfort, physical phenomena simulation

INTRODUCTION

Integration of Simulation Domains

Computational simulation tools use various models to simulate aspects of environmental performance. Either these tools address only one specialized domain, or a number of specialized models are joined together in a simulation toolkit. Interoperability, coupling and integration of models, mainly on the level of the object description have been applied (discussion see e.g. Citherlet 2002) with the objective to simplify modeling and to reduce model entry effort. In coupled and integrated models, the interaction of separate domain models during the simulation run is implemented.

However, the physical world is much more involved than represented in such programs. Occupants' comfort perception and comfort relevant building behavior are results of a highly integrated set of physical phenomena and human-environment interaction.

Furthermore, comfort quality of the environment is a spatial phenomenon. Thermal, visual and aural perception and air quality are defined by distribution of material, energy, moisture and various contaminates in space (Schwede 2006a).

Although building behavior and human-environment interaction in the physical world are complex, current application of computational simulation is restricted to targeted investigation, of known or anticipated issues within a limited set of domains. In contrast to domain-specific simulative investigation, diagnostics in the built environment after occupancy is able to uncover unexpected performance shortcomings and harmful building behavior across the various design and engineering domains (Luther and Schwede 2006).

This paper presents an approach towards modeling of various physical phenomena in a highly integrated manner in one representation. It is the objective to develop a digital representation of the physical world, in which physical laws are valid and in which highly integrated physical behavior can be investigated in the digital world before the design object itself is available in the physical world.

Integration in the Design Process

In the conventional design process the expected behavior of the design object is determined through human interpretation of a representation of structure under application of conventional tools. In the performance-based digital design process the expected behavior is simulated and displayed with a computational model integrated in the design development process and the simulated behavior is interpreted in regard of the design objects performance.

Both design processes are depicted in Figure 1 in adaptation of Gero's FBS-framework (1990). In order to integrate computational analysis in the design process the interplay of the structure representation S and the simulation model M has to be seamless.

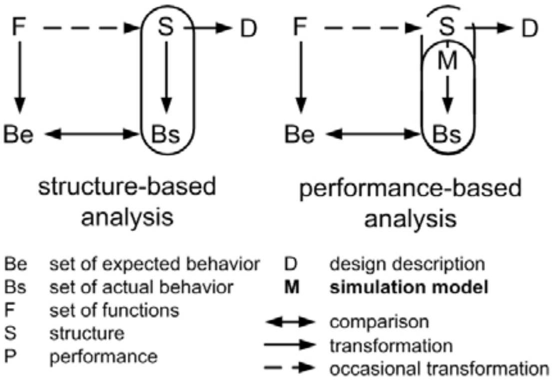


Figure 1 left: structure-based analysis right: performance-based analysis in function-behavior-structure notation (Gero 1990)

In this context Marsh (1997) formulates as aims for his simulation tool development to overcome the separation between design and analysis, to make the process of entering data part of the design process, to let the creation of a simulation model replace the act of sketching and to be able to deal with inhomogeneous developed designs.

Although designs are developed continuously and various degrees of definition including inhomogeneous advanced designs occur during the design process, most available simulation tools require a data rich design description with a strictly defined structure and degree of definition. Therefore in order to support design activity effectively simulation models have to be able to translate inhomogeneous advanced structure representations into statements about the expected physical behavior of the represented structure.

While Marsh (1997) emphasizes the development of the frontend and employs existing or newly developed but demanding simulations models, Suter and Mahdavi (1998) suggest seeing the representation and simulation models closer connected. They state that a simulation model should be seen as special kind of representation, which includes a description of the artifact and predictive algorithms to calculate aspects of the artifacts behavior. In their following work (1999) they differentiate between primitive-geometry, component-based, and space-based representations, and they present a framework (2003) for seamlessly translating between a solid-based representation and a sheet-based representations in order to supply geometry and material information for volume-oriented and object-oriented simulation models based on basic geometry specifications. Although the internal processing seems to be rather involved the structure representation itself is undemanding and adaptable.

Schwede (2006a, 2006b) suggests that future simulation models should not require a specialized design frontend, but that the simulation model itself should be undemanding and adaptable in order to be processed based on design descriptions generated with the design tools of choice. He introduces the concept of a geometrically and physically self-contained digital design space in which designers can develop their designs simply by placing objects and by defining their materials.

The principle of geometrical selfcontainedness ensures that all geometric relations, which can be determined on basis of such simple descriptions, are calculated internally by the computational system. The principle of physical selfcontainedness means that physical behavior is modeled through a selfcontained system of equations and algorithms. Such a physically selfcontained model only requires a small set of parameters as input, as all physical phenomena are formulated as functions of these basic parameters and are calculated internally.

The application of both principles ensures that no complex and scientific reasoning, outside the architect’s world of thinking, is required at design time to develop the design under application of computational simulation. The design object is defined with a rather simple description of its geometry and its material.

Only two additional concepts are required to run the simulation: activities, representing sinks and sources of the modeled physical phenomena, and sensor object used to access simulation results at specific locations of the three-dimensional design space.

Scope of the Simulation Model

Comfort is a complex response to the environment. It is not only a multi-dimensional perception itself but also situated, depending on the previous experience of the occupant.

A literature review (Schwede 2006a) revealed that a three dimensional, dynamic and integrated representation is required to assess the comfort quality in future environments. The physical environmental phenomena, which have to be modeled to assess the physical aspects of comfort, are:

- temperatures,
- humidity,
- air contaminates,
- CO_2 content,
- air flow,
- light, and
- sound.

Additionally to the distribution of these phenomena, resulting material properties must be calculated as function of the material parameters.

CONCEPT AND MODEL

Physical behavior is a space-based phenomenon, independent from object concepts designers use to develop designs. The physical behavior of an object can be observed through the transient spatial distribution of physical states. It is a function of the distribution of material and the various physical states in space.

Exchange between areas is driven by the gradients between their physical states and constrained by the properties of their materials. Properties of material change with their physical conditions. Furthermore multiple exchange processes between areas take place simultaneously.

In this research multi-dimensional physical behavior of the design object is modeled as a phenomenon emerging through interaction of simple and discrete elements representing material in space. Spatial elements are modeled as 'congeneric cells' and their interactions are modeled through the concept of 'congeneric conjunctions'. The data structure of a 'congeneric cell' stores the physical state information and its model comprises functions to calculate the dynamic properties of their material.

Two types of 'congeneric conjunctions' are implemented as shown in Figure 2. Near-conjunctions connect directly neighboring cells and remote-conjunctions connect cell surfaces, which are in view contact. Near-conjunction are used to model conduction, diffusion and flow processes, while remote-conjunctions represent radiation, light and sound exchange.

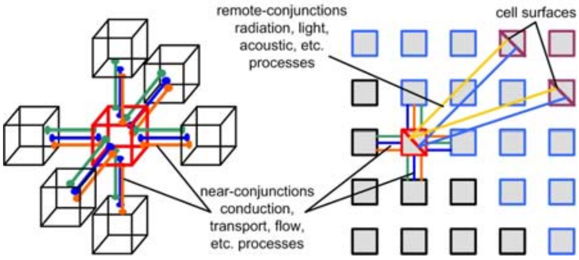


Figure 2 conjunction concept: left: near-conjunctions, right: near- and remote-conjunction

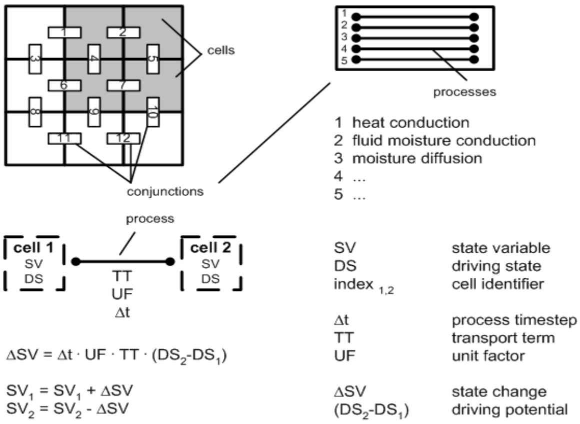


Figure 3 implementation of the conjunction concept and exchange processes

Near-exchange processes are modeled as sets of linear equations in the conjunction dataset as shown in Figure 3. The implementations of remote processes between cell surfaces follow the radiosity approach.

The various process datasets are entered in a common list of transport events as shown in Figure 4. An individual internal process timestep is calculated for each event. The list is stepped through during the simulation and the calculation of specific transport events is triggered at the appropriate time defined by the simulation progress and the internal timestep.

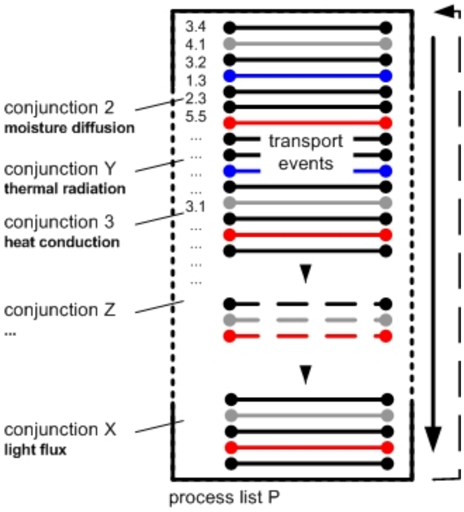


Figure 4 common process list of transport events

The cell states result from the transport processes or they are set by activity datasets, entered in the model to represent sources or sinks of physical phenomena. Cell properties are updated during the simulation, and properties of the conjunctions for all represented physical phenomena are re-calculated continuously with the updated material properties.

ASSESSMENT AND TESTING

Description: Application

The translation from the object-oriented design description into the depictions of the simulation results is shown in Figure 5:

(1) shows the object model as designed in an early stage of the design process. In (2) external and internal activities, such as heat sources and light sources, are entered as additional properties attached to the objects. (3) Data points and sensors to read simulation results during the simulation run can (but do not have to) be entered. After the modeling is complete the object model is translated into the cell and surface model (4). Following the near-conjunctions and the remote-conjunctions are

established automatically in (5) and the constant exchange parameters and constant material properties are calculated and stored in the model.

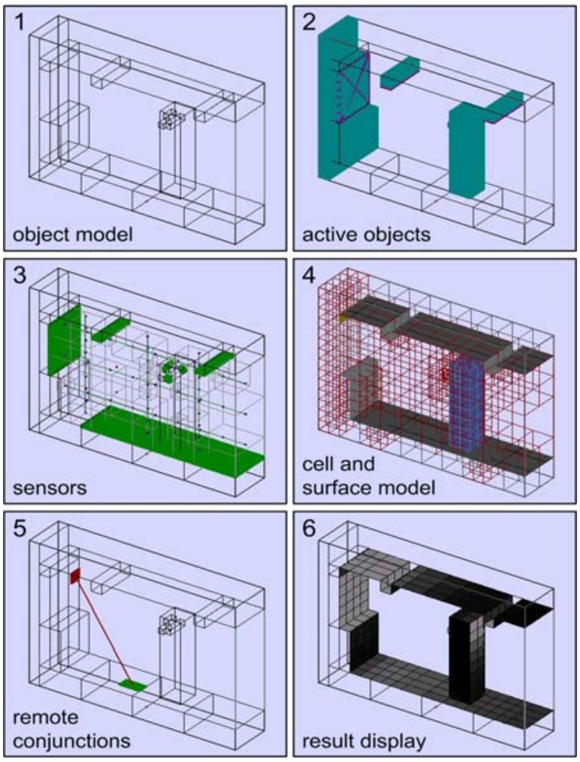


Figure 5 translation from the object-oriented design description into the simulated result display

When the translation of the design description is complete the simulation is run. (6) shows results of the light model as example for the multiple possible result displays.

Assessment: Concept

The concept was tested through implementation of a prototype, including model input functions, model translator functions, simulation engine and result output functions. The workflow between object model entry and simulation results display was implemented successfully.

However at this stage of development only models of the size of a small office room, with an effectively small number of cells, surfaces and conjunctions can be translated and processed due to computational constraints. The translation algorithm requires too much time to be used in a realistic design process.

The physical model, as implemented in the prototype is able to simulate conduction and diffusion processes using the near-conjunction concept and light and thermal radiation employing the remote-conjunction concept. It was not possible at this stage to implement a working flow model in the structure of the explored representation.

Testing: Simulation Model

In the following section two implemented physical phenomena are demonstrated. The first is heat conduction in an aerated concrete beam representative for the group of near-conjunction processes. The second presents the light model as example for the remote-conjunction processes.

Further discussion of these test cases and additional tests can be found in (Schwede 2006a).

1. Heat Conduction Model

One-dimensional heat conduction in an aerated concrete beam is modeled as a test case for the conduction model with dynamic material properties. At the beginning the humidity is uniformly distributed throughout the beam. A temperature source in the middle of the beam oscillates between 5 and 35°C within 24h.

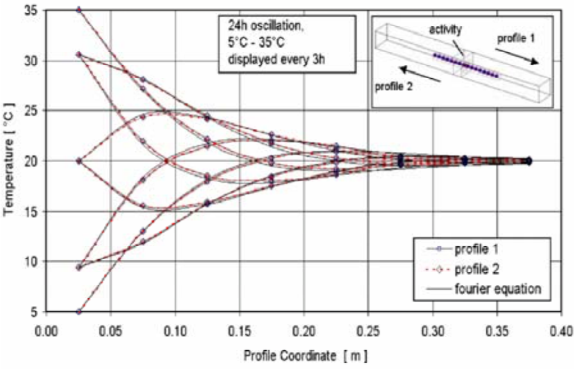


Figure 6 test of the conduction model: heat conduction in aerated concrete beam (50% relative humidity) with central oscillating heat source

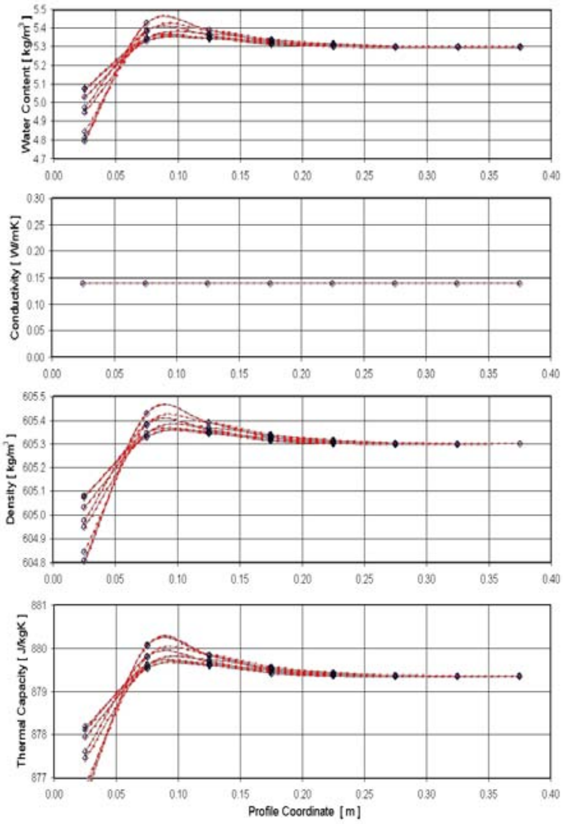


Figure 7 water content and resulting material properties for the test case depicted in figure 6

Figure 6 shows the results of the dynamic simulation as temperature profiles on both sides of the heat source every three hours. Additionally the temperature profile calculated with a Fourier equation is displayed.

It is shown that the results of the cell model and the Fourier model match well. It is also shown that the cell model produces symmetric results on both sides of the heat source, which indicates that the order in which the transport events in the list of transport events (see Figure 4) are processed does not affect the simulation results.

Figure 7 shows the resulting moisture distribution and the material properties calculated dynamically and displayed with lines for the results every three hours.

2. Light Model

The illuminance distribution at floor level is simulated for five office room geometries. The light source is a window in a short wall of the room and room surfaces are modeled uniformly with 75% reflectivity. The window is modeled as a diffuse light source of 3580 cd/m^2.

The simulation case geometries are shown in Figure 8 and the calculated illuminance profiles from the façade into the room for cases M1 to M5 are depicted in Figure 9.

Case M6, shown in Figure 8, investigates the distribution of light on the desk next to the window. Two different modes of result representation for this investigation are shown in Figure 10.

The results of the light simulation show reasonable results.

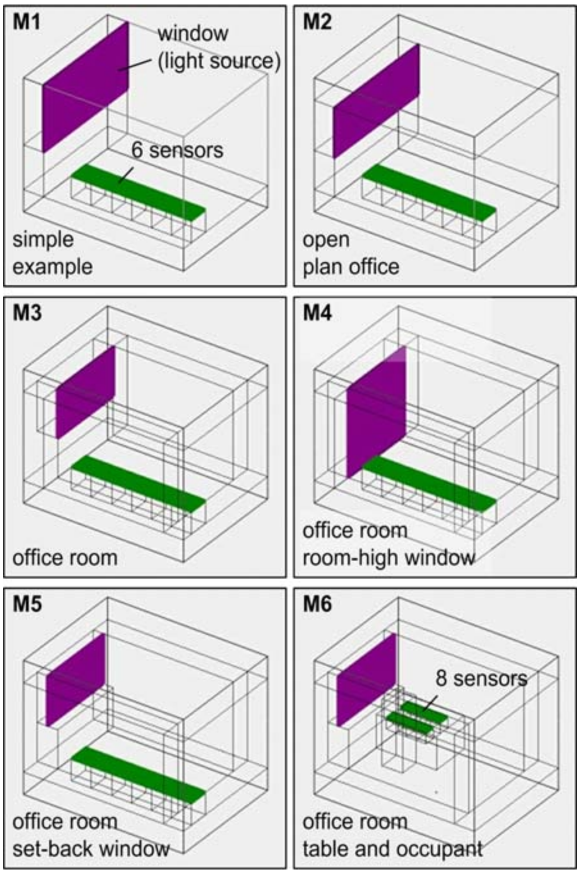


Figure 8 test of the light model: geometry of test cases, location of light source and sensors

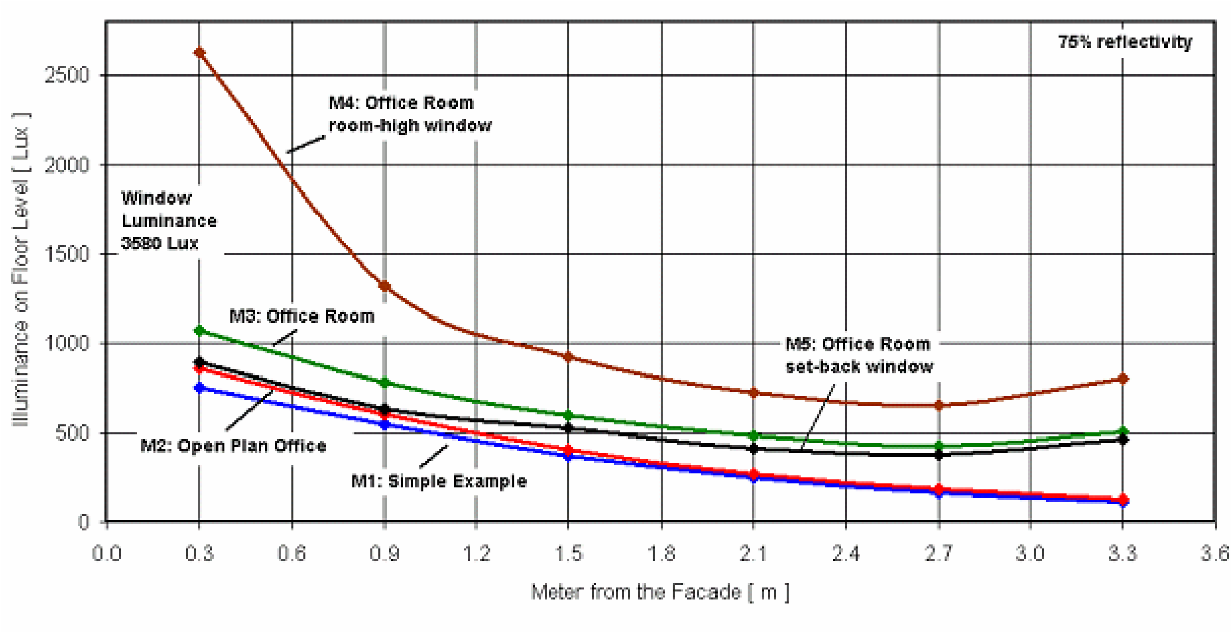
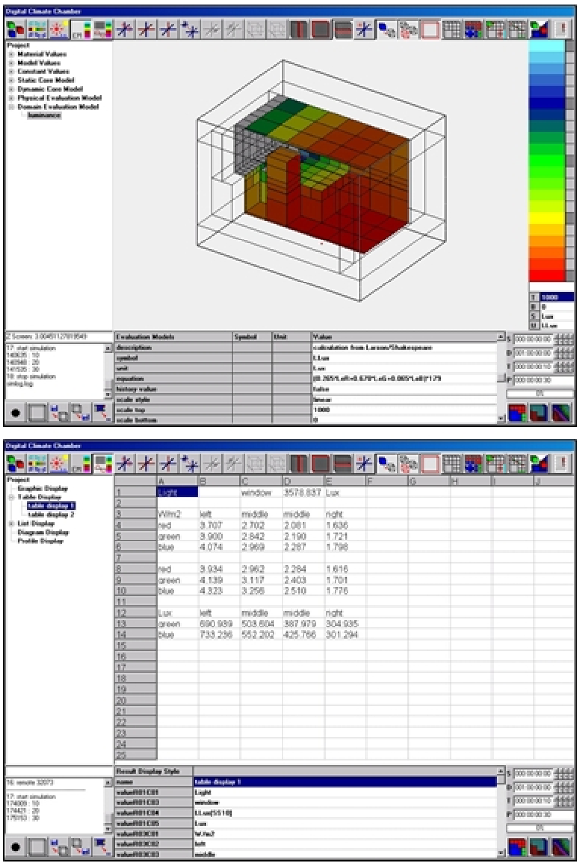


Figure 9 comparison of light distribution in the office room, test cases: M1-M5, figure 8



Evaluation Models	Symbol	Unit	Value
description			calculation from Larson/Shakespeare
symbol			LLux
unit			Lux
equation			(0.265*LeR+0.670*LeG+0.065*LeB)*179
history value			false
scale style			linear
scale top			1000
scale bottom			0

	A	B	C	D	E	F	G	H	I	J
1	Light		window	3578.837	Lux					
2										
3	W/m2	left	middle	middle	right					
4	red	3.707	2.702	2.081	1.636					
5	green	3.900	2.842	2.190	1.721					
6	blue	4.074	2.969	2.287	1.798					
7										
8	red	3.934	2.962	2.284	1.616					
9	green	4.139	3.117	2.403	1.701					
10	blue	4.323	3.256	2.510	1.776					
11										
12	Lux	left	middle	middle	right					
13	green	690.939	503.604	387.979	304.935					
14	blue	733.236	552.202	425.766	301.294					
15										
16										
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25										

Result Display Style	
name	table display 1
valueR01C01	Light
valueR01C03	window
valueR01C04	LLux[5510]
valueR01C05	Lux
valueR03C01	W/m2
valueR03C02	left
valueR03C03	middle

Figure 10 different modes of result representation: false color picture and table, test case: M6, figure 8

CONCLUSION

The presented research explores an approach towards a digital integrated representation of various physical phenomena, which can be employed to augment digital design representations with information about the future multi-dimensional behavior of design objects.

This exploration is motivated by the presumption that its application would help to close the gap between design and performance evaluation. Such a universal representation, which could inform a range of questions, of which not all are known when the investigation is started, let alone which are not known when the simulation tool is developed, would acknowledge the ill-defined characteristic of problems in the architectural domain. Such a model would, if integrated in the design process, be able to influence the design outcome in an interactive discussion of the design objects performance with the designer. This paper presents the rationale, concept and a test implementation of such an integrated and universal representation.

Physical phenomena necessary to assess comfort are modeled in a highly integrated manner in a volume-based representation. The components of the model, ‘congeneric cells’ and ‘congeneric conjunctions’, for near- and remote-processes are described.

The principles of geometrical and physical self-containedness are introduced and employed to avoid that circumstances, which can be determined automatically have to be specified at design time. Thereby the modeling demand is reduced so that designers can develop designs using familiar concepts. Only the geometry of objects and a label for their material has to be entered. Additionally active objects, representing sources and sinks, and sensors can be specified.

The paper demonstrates the general feasibility of the approach with tests for one near-distance process, namely heat conduction in moist aerated concrete, and a remote-distance process, namely the simulation of light.

Although the developed representation is not applicable in a real design process, and although not all physical phenomena have been implemented successfully, a contribution towards better integration of computational simulation and towards the simulation of highly integrated physical phenomena as necessary for comfort assessment has been made.

ACKNOWLEDGMENT

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