A DIGITAL BRIDGE FOR PERFORMANCE-BASED DESIGN

Simulation of building physics in the digital world

DIRK A SCHWEDE
The University of Sydney, Australia

Abstract. The augmentation of digital design representation with programmed analysis capabilities can result in a shift from structure-based to performance-based designing. This paper presents a system to translate a simple digital structure representation into information about the multi-dimensional highly integrated and dynamic physical behavior of the design object. The user interface uses an object-oriented representation familiar to the designer, while the physical behavior is calculated internally with an abstract and space-based model formulated in form of a constructive language. The system is intended to serve as a "digital bridge" in the circle of design activities to enable performance-based designing.

1. Introduction

1.1. DIGITAL AUGMENTATION

Digital augmentation of design representation with programmed analysis capabilities can support the architectural process by translating the structure of the design object into more complex property and behavior information, than can be obtained by human reasoning alone.

Such information can support a more integrated understanding of the behavior of the of the design object, so that knowledge about the designed structure and about its actual behavior (performance) would become closer connected in the analysis and evaluation process. This could result in a shift from a structure-based to a more performance-based design approach.

Figure 1 shows the design process in the notation of Gero's FBS-framework (Gero 1990). In extension of Gero's set of design activities, the simulation model generation, as it occurs in the augmented design process, is included in right depiction. The performance is represented by the set of actual behavior information Bs in the original notation of the framework.

J.S. Gero (ed.), Design Computing and Cognition '06, 23–40.

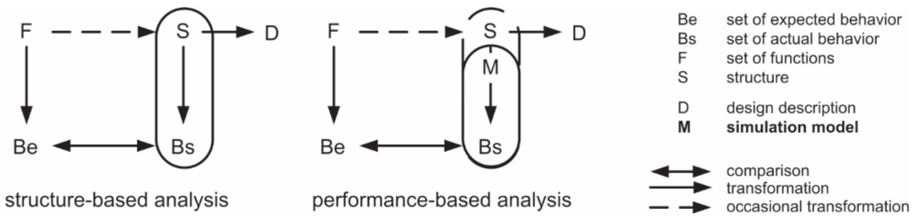


Figure 1. Left: analysis the structure-based, not augmented (Gero 1990) and right: in the performance-based, augmented design process.

The figure shows the analysis activity in the structure-based design process in comparison to the analysis in the performance-based design process. The prediction of the structure's actual behavior is not based on the analysis of the structure alone but on information about its performance, conceived by computational simulation of the structure's properties and its dynamic behavior interacting with its environment.

In the digital design process the simulation model generation is as far as possible a programmed and automated activity on basis of a digital structure representation, in a form understandable and editable by the designer. While the simulation is far beyond, what the designer can achieve by reasoning, the display of the results is near the designer's experience and domain language. Thereby simulation functions as a "digital bridge" in the circle of the performance-based design process.

This paper is concerned with the digital support of the analysis activity in the human design process. It is not concerned with automatic evaluation and the digital generation of design suggestions (synthesis).

This paper describes a digital system, which translates a three-dimensional structure description into information about its dynamic physical behavior using a highly integrated and self-contained physical model to represent physical phenomena required for comfort quality assessment of buildings.

1.2. COMFORT ASSESSMENT REQUIREMENTS

A literature survey on available comfort models (Schwede forthcoming), using the building-in-use post-occupancy-method (Vischer 1989) to define the scope, revealed that the assessment of physical aspects of comfort requires a three-dimensional, highly integrated, simultaneous and dynamic representation of the following phenomena:

- temperature,
- moisture content,
- CO_2 content,
- odorous substances content,
- velocity,

- light, and
- sound.

1.3. AVAILABLE SIMULATION TOOLS

Such highly integrated models of phenomena and their dynamic behavior are not available at the current stage. Building simulation implementations represent physical phenomena required to assess the thermal conditions in node- and building-zone-based models with a low resolution of the physical phenomena.

Models of other physical phenomena, such as light and sound, might be available in simulation tool suites, which provide assess to common modeling and result display functions, but which operate several separate or loosely coupled simulation engines on basis of one building model database (e.g. Marsh 1997; ESRU 2002). More integrated simulation models are constrained to specific views and two-dimensional representations (e.g. Künzel 1994) or to steady state calculations.

Integration of various domain models on basis of a common database is discussed as one of the key problems of the application of simulation in the design process. Mahdavi (1999) uses a space based-representation in the implementation of the simulation suite SEMPER in order to translate seamlessly between a shared object model and domain object models (thermal and flow model). In SEMPER the design object is modeled in a spatial grid (e.g. $1x1x1m^3$) and the grid cells are simulated similar to building zones in other simulation programs. Walls, for example, are represented as a linear sequence of nodes in the thermal simulation model.

In more recent work Suter and Mahdavi (2003) use a sheet representation (SHR) and a solid representation (SOR), in order to supply node-based models as well as space-based models (e.g. FEM-models) with information from the shared object model. They apply a space-based technique for the mapping between these representations.

Nevertheless the literature review on comfort assessment models, cited earlier (Schwede forthcoming), revealed that the integration and the simultaneous simulation of physical phenomena is required for the assessment of the comfort conditions, rather than the operation of separate simulation models on basis of a central data model. Therefore the research presented in this paper aims to integrate on the level of the simulation engine, rather than on the level of the data model.

1.4. PHYSICAL BEHAVIOUR

Physical behavior is a function of material in space and the physical state of the world. This behavior can be described with well-known physical laws, is modulated by physical properties of the space and driven by differences of the physical state in neighboring areas. The physical state is the result of transport processes and storage phenomena (or of chemical reactions) at the location. Physical behavior is not a function of object-oriented concepts, which humans use to describe objects in the physical world.

Conrad Zuse (1970) discusses the idea of a calculating space and suggests using automata concepts to describe physical phenomena. He understands the calculating space as a theory to describe our world in the quantum paradigm alternatively to conventional physics. Fredkin (1992) argues even further for the paradigm of a finite nature, he assumes that at the end everything, including space and time, will turn out to be atomic or discrete and that there is a fundamental process of physics, which is computation universal. He states that there are no solutions in closed form, similar to the ones in physics and that nothing can be calculated faster with the same resolution than to do the simulation step-by-step.

However the reasonable size of a quantum to describe physical processes in architecture is compared with the scale Zuse and Fredkin suggest to explain the world as such, of macroscopic scale. The smallest length designed and plotted in architecture drawings is 1 mm. The fabrication accuracy on the building site is 1 cm for massive constructions and 1 mm for the steel work and fit out.

Nevertheless the understanding of physics as a system of interacting simple and discrete elements representing material in space, is (under application of digital technology) able to overcome complexity introduced in the simulation models by object-oriented representation concepts.

2. Concept

2.1. CONSTRUCTIVE LANGUAGE

The simulation model is developed in form of a constructive language to ensure its universal and context-independent applicability, so that various questions about the physical behavior of the design object (of which not all are known, when is model is developed) can be answered on its basis, to allow its processing on basis of various design representation and to enable a demand-oriented result display.

A set of basic spatial elements is created, which displays different meanings according to the physical state calculated for their locations, when the objects synthesized from them are looked at from different domain viewpoints. Not only the topology of the basic elements and the context determine the meaning of their combination, but also the multiple inherent properties of the elements and their conjunctions.

The constructive language to simulate physical behavior of material in space is defined by the following components and their concepts are explained in the following paragraphs:

• basic elements	congeneric cells with physically self-contained behavior map
• rules of topology	geometrically self-contained design space
• rules of validity	demand-oriented validity range
• meaningful context	evaluation models

2.2. GEOMETRIC MODEL

The geometrically self-contained design space sets the spatial boundaries in which the design takes place at the beginning of the design session. Initially it contains material with meaningful properties (e.g. air) and the conditions inside the design space and at its boundaries are defined (e.g. weather). Design activity changes the content of the design space by adding geometric objects within its boundaries, but does not extend it spatially.

The concept of geometrical self-containedness ensures that only designable model content of the geometric model has to be specified at design time. Not-designable model content can be determined automatically as the geometry is represented in a space-based and closed form.

2.3. SIMULATION MODEL

Congeneric cells represent volume and surface properties and storage phenomena, while congeneric conjunctions represent transport processes in the model. Together they represent the physical behavior of the design space.

The physically self-contained behavior map represents the dynamic properties of the cells' material as a function of the cells' material and its physical state. The simulation model is valid for physical states within the validity range.

2.3.1. Physical Self-Containedness

The concept of physical self-containedness represents the fact, that the physical behavior of the world is a result of an inseparable system of interrelated and simultaneous physical processes. The model is based on a set of well-known physical laws and complete and integrated enough to calculate the system of physical phenomena without any implementation of their interaction at design time.

2.3.2. Congeneric Cells

The design space is dismembered into a three-dimensional structured grid of cubic cells. Physically self-contained behavior maps for each cell volume are allocated, according to the material at the cells' locations. The congeneric cells' behavior is well defined by physical laws and only dependent on the cells' properties, their history and their boundary conditions. The cell properties are dynamic functions of the cell's geometry, material and its physical state, Figure 2.

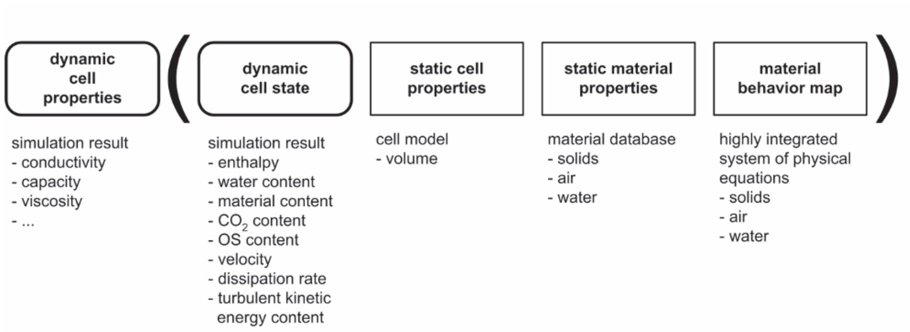


Figure 2. Calculation of dynamic cell properties.

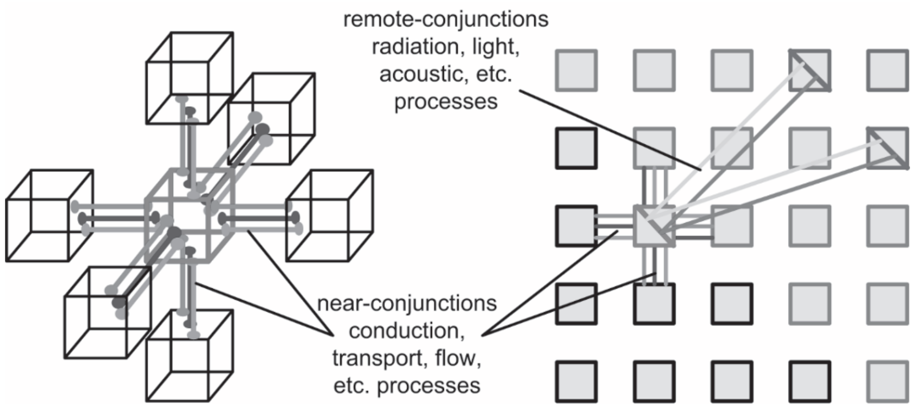
The physical state is either a result of the previous condition or it is set to a designed value at the beginning of each time step, if an activity property is allocated to the cell. The concept of activities allows modeling sources and sinks of the represented physical phenomena, such as for example light emitter or heating elements.

At any point in time a cell only "knows" its own state and properties. The boundary conditions of each cell are given by the physical state of their neighboring cells. The interaction between two cells is modeled by congeneric conjunctions.

2.3.3. Congeneric Conjunctions

Congeneric conjunctions represent exchange between the cells or between the cell surfaces. Near-conjunctions connect spatially adjacent cells. Remote conjunctions connect the cell surfaces that can "see" each other but are separated by transmitting material (e.g. air) between them, Figure 3.

The mathematical formulations of the conjunctions are simple and of common structure, for the various processes, so that transports of various kinds can be calculated with a, as far as possible, common algorithm. The structure of the mathematical formulation is depicted in Figure 4.



(a) (b)

Figure 3. Concept of congeneric conjunctions:
(a) near-conjunctions, and (b) remote-conjunctions.

The near-conjunction primary processes represent conduction, diffusion and flow phenomena. Convective transport phenomena associated with these processes are modeled as secondary processes. Heat radiation, light and sound are modeled as remote-conjunction processes.

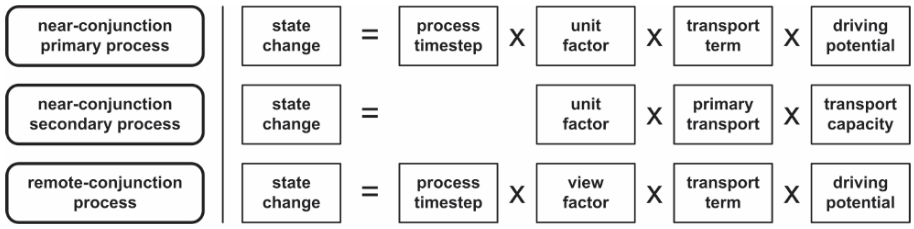


Figure 4. Structure of the mathematical formulation of conjunction processes.

As example the data structure of the transport processes of near-conjunctions between two cells are shown in Figure 5. A near-conjunction connects two cells and contains a vector of process datasets.

Each process dataset is connected to the state variable and the driving state of the process it represents in the cells' datasets. It contains the transport term (resistance) and a process-individual calculation timestep (frequency).

The transport term is calculated as a function of the dynamic properties of the two cells and the cells' geometries. The process-individual timestep is calculated each timestep as a function of the transport capacity of the cells and the transport resistance of the process dataset in order to avoid oscillation of the calculated cells' states.

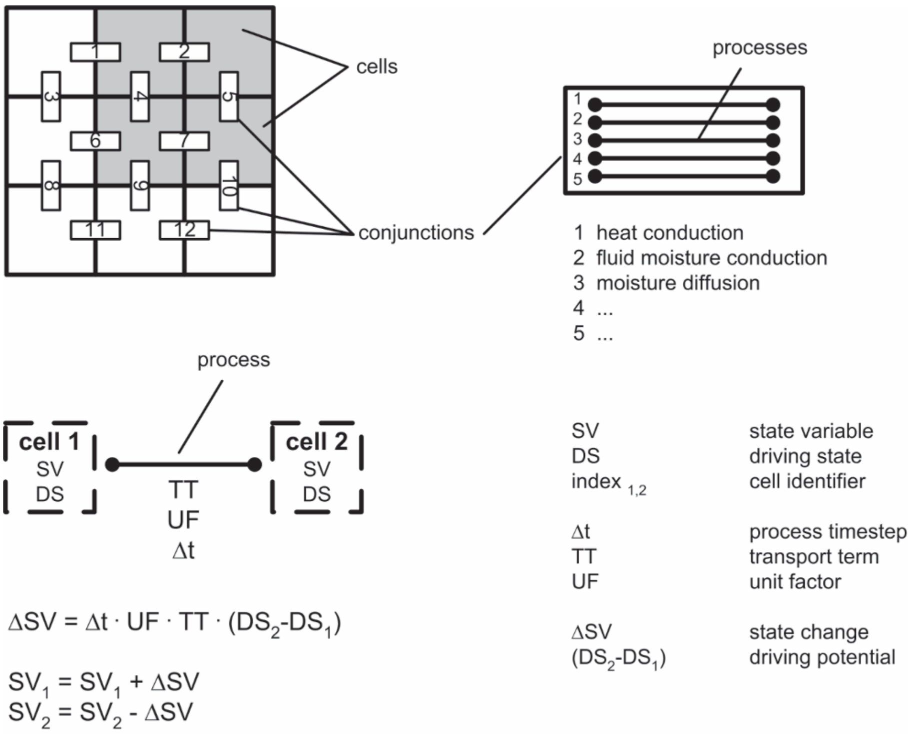


Figure 5. Depiction of the data structures of the model (cells, conjunctions, processes).

2.3.4. Simulation Engine

For the simulation of the structure's dynamic behavior the process datasets of each conjunction are copied into the central process list as depicted in Figure 6. The process-individual timestep Dt and the number of calculations C per overall-timestep DT are determined. The counter variable c is set zero at the beginning of the overall-timestep.

The algorithm steps through the process list repetitively (multiple times during one overall-timestep) during the simulation. The variables cc and C_{max} of the list and c and C of each process are used to trigger the calculation of the individual processes at the appropriate moment during the simulation timestep as shown as C++-code in Figure 6. The process list is processed repetitively until all exchange events are calculated as often as required.

An exchange event changes the state of both cells engaged in the process. The cell and conjunction properties are updated at the end of each simulation timestep.

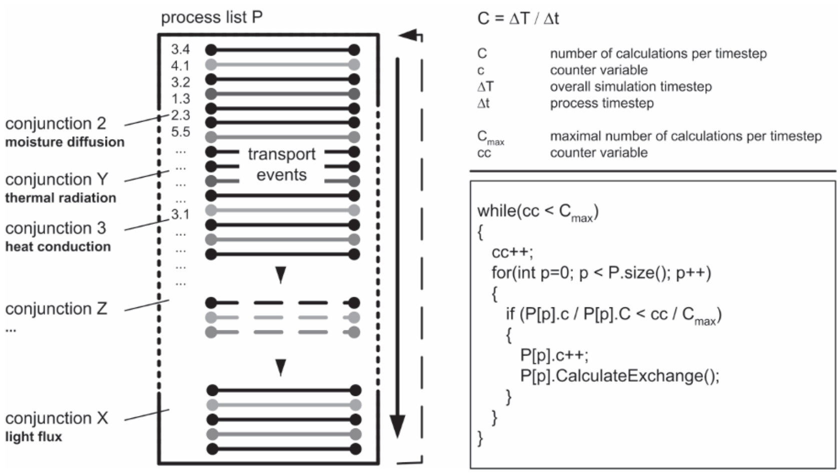


Figure 6. Repetitive calculation of the process list within one timestep.

2.3.5. Validity

The rules of validity specify the limits of physical parameters necessary to assess comfort and limit the calculation to the conditions the equation catalog of the cells' self-contained behavior map is valid for.

2.4. ACTIVE BEHAVIOR MODELING

Activity models are assigned to objects in order to make them a source or a sink of physical phenomena, such as a heat source or light emitter. They are modeled as constant values, as equations with simulation parameters and simulation results as input or their values are read from a file. During the simulation the state of an active cell or an active cell face is set to the designed value. The concept of activities allows modeling internal sources and sinks as well as the conditions at the boundaries of the design space, Figure 7.

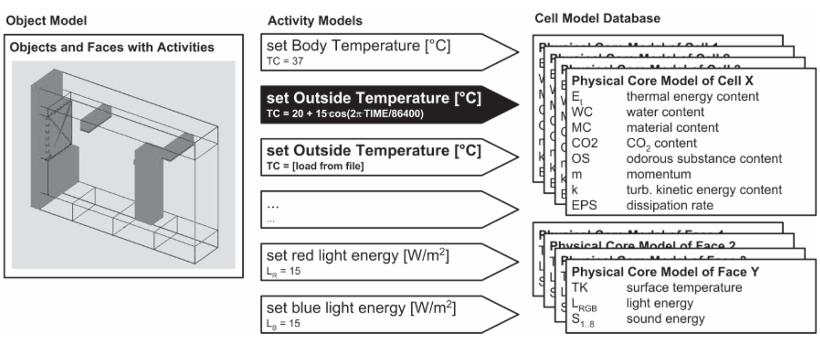


Figure 7. Modeling function for activities.

2.5. EVALUATION MODELS

The concept of evaluation models allows customizing the result display for the context of the investigation and individually for the demands of the investigators. Meaningful views on the design space's physical behavior can be synthesized by modeling evaluation models as equations with parameters of the simulation model and simulation results as input, Figure 8.

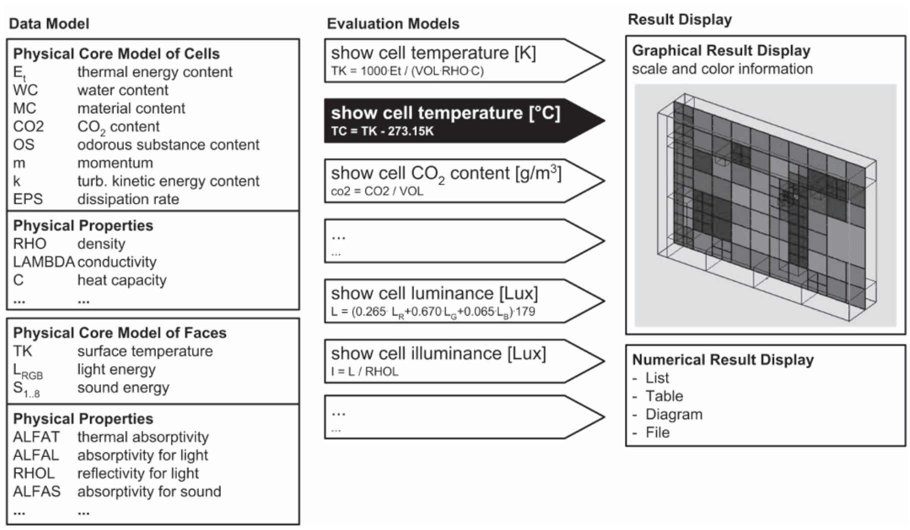


Figure 8. Formulation of evaluation models.

Sophisticated and integrated evaluation models can be formulated using several of the simultaneously calculated physical phenomena as input. A simple comfort evaluation model for the three-dimensional false color display could be formulated as, Figure 9:

		$T_{°C}$	<	20°C	too cold,	display in shades of blue
20°C	<	$T_{°C}$	<	26°C	comfortable,	display in shades of yellow
26°C	<	$T_{°C}$			too warm,	display in shades of red

While the three-dimensional false color display are applied for qualitative assessment, datapoints, surface sensors and balance volumes, which are modeled as virtual sensing objects in the geometric model, are used to read results for quantitative assessment from the simulation.

3. Implementation

The concept was implemented and tested on Pentium 4 notebook with 2.5GHz and 1GB memory in C++ in a Windows XP environment, using Borland C++ Builder 6 and OpenGL for the user interface implementation.

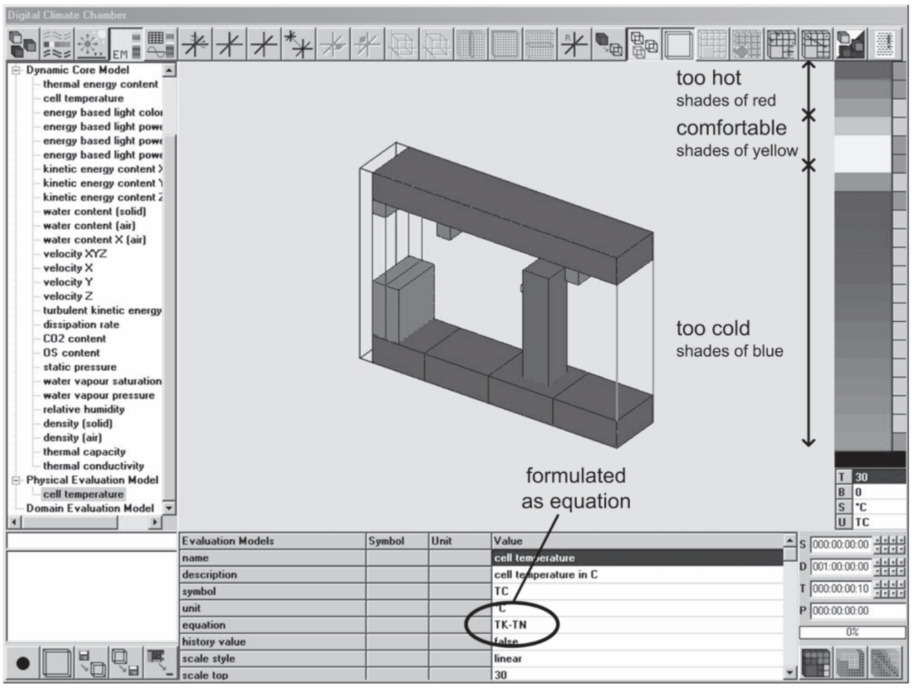


Figure 9. Screenshot of the user-interface for modeling evaluation models.

The prototype consists of three main parts the user interface, the model translator and the simulation engine, of which the user interface is used for the design functions as well as for the result output and evaluation. Figure 10 shows the schema of the prototype implementation.

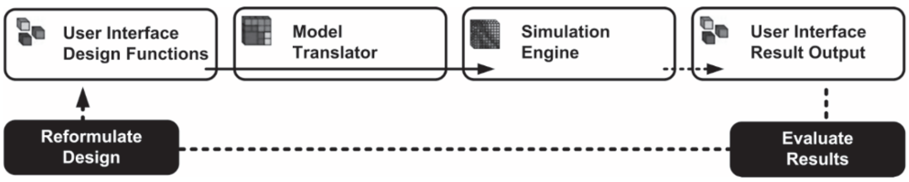


Figure 10. Schema of the prototype implementation.

3.1. DATA MODEL

Although a modeling interface to enter the geometric model was implemented in the system for the model development, the concept and the model translator algorithm would allow modeling with other design tools, which are able to provide the following basic information about the design object's geometry and properties:

•	geometry	physical objects virtual objects (sensors)
•	identifier of geometry-related properties (label)	material active behavior

Additional system specific information is required for the result output and the content of the material, activity and evaluation model database. This information is provided in project independent databases:

•	display functions	evaluation models result output functions
•	detailed property information	material activities

3.2. MODEL TRANSLATION

The model translation involves a sequence of steps from the object model entered by the user into the cell and conjunction model.

The object model is associated with a volume representation as shown in Figure 11. A volume is a tetrahedron, which's four points define four planes, each of which defines two halfspaces. Simple halfspace operations are applied in the successive steps of the translation algorithm (see C++ code in Figure 11) to test for example, if a test point is in or outside an object.

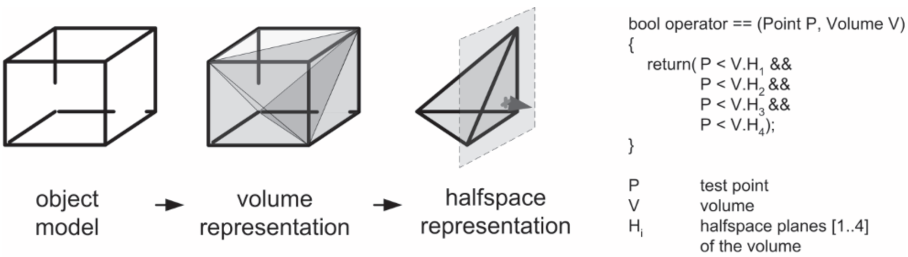


Figure 11. Representations of the object model in the prototype implementation and formulation of halfspace-operation as C++-code.

In Figure 12 the steps of the translation from the object representation into the structured-cell grid representation are depicted in step 1 to step 4. Step 5 depicts the near-conjunctions and step 6 the generation of the cell faces. The further steps (remote-conjunction generation, connection of sensors and activity datasets, setting of start values) are omitted as the detailed explanation of the translation process is beyond the scope of this paper.

Although the prototype does only allow designing with rectangular object, the concept of cells and cell faces would allow the representation of objects with sloped faces. While the cells follow the rectangular shape of the cell grid and would partly overlap with the object's edges, the cell faces are oriented and positioned like the object faces they are associated with as sketched in Figure 3.

An algorithm for the translation of models with sloped faces was developed during the research. It was not implemented in the final prototype implementation due to long processing times and insufficient robustness.

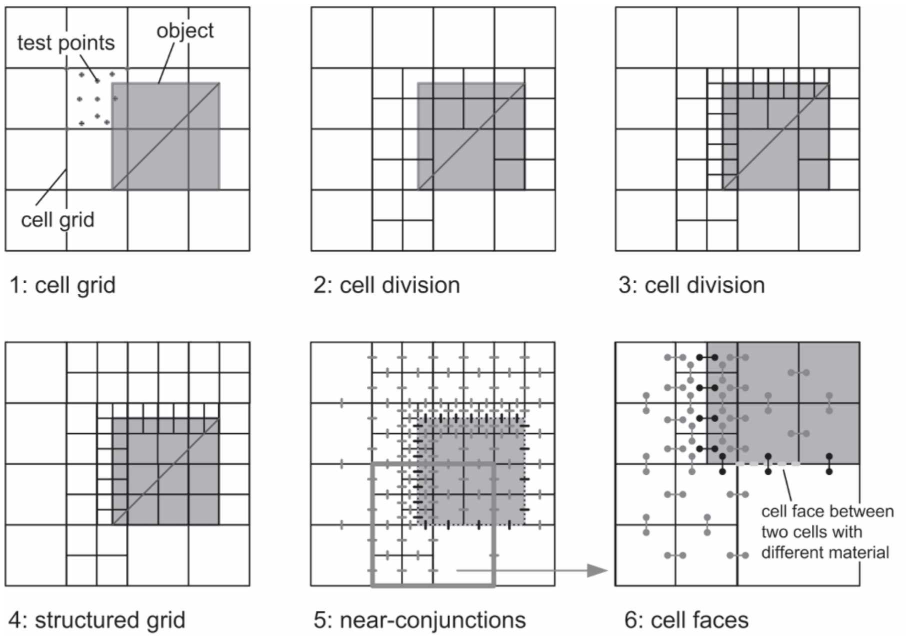


Figure 12. Translation of the object model into the cell model, generation of conjunctions and cell faces.

4. Application

Figure 13 shows the application of the self-contained model in the design process schematically. Figures 14 and 15 illustrate the process with a short sequence of screenshots, showing the "design" of an office room as application example.

Initially the design space is filled with air, Figure 14, (1.1), and then the outdoor conditions are added in form of an object with active behavior (1.2). Following the designer enters the first design suggestion (2.1) and translates the model in the cell representation (2.2, which would not be displayed to the designer in the design process).

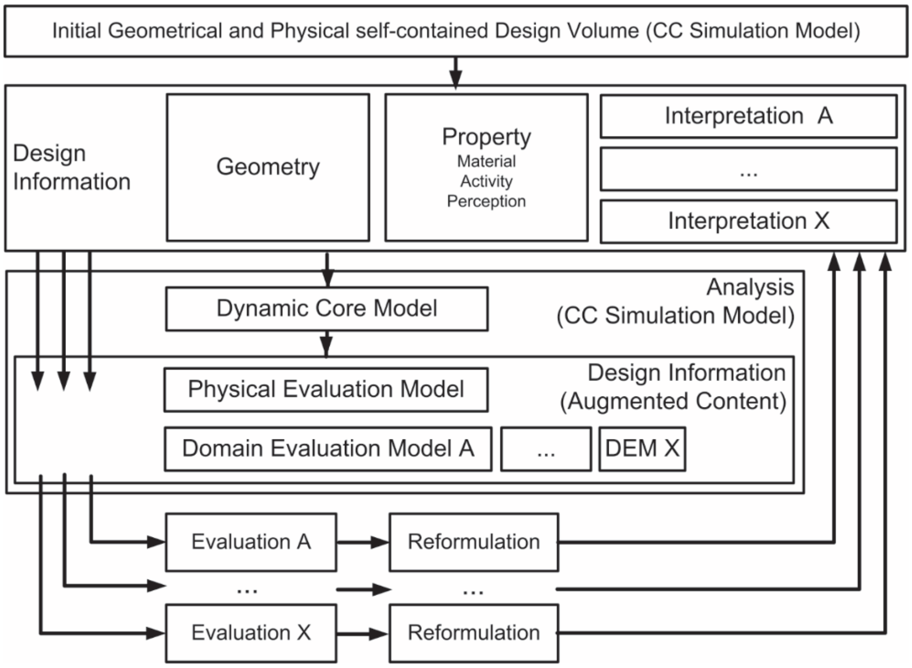


Figure 13. Application of the self-contained Model in the Design Process.

A first simulation would reveal that the temperature near the window is uncomfortable cold (2.3), and that the daylight conditions are acceptable (2.4), but that additional light is required in the depth of the room. More results of the integrated model could be reviewed to understand the shortcomings and qualities of the design proposal's performance.

At this stage a qualitative assessment is sufficient and the 3-dimensional depiction allows fast and detailed understanding of the problem.

In the following step the design is improved (3.1). A heating element is added under the window and light fittings are added at the ceiling. The light fittings are modeled as light sources, but do also introduce heat in the room.

Additionally an occupant is entered in the space (3.1) as heat and air contaminate source. Further sensing capabilities of the body to evaluated non-uniform thermal conditions and at the position of the eyes to assess glare are added.

Figure 15, 3.2 highlights the object with active behavior. After the changes of the geometric model are entered, the model is translated into the cell model. Plate 3.3 shows the remote-conjunction generation (which was also performed, but not displayed, for the first simulation run).

The second simulation shows, that the heating element and the heat emission of the other sources prevent the room from cooling down and that the light conditions in the depth of the room have improved.

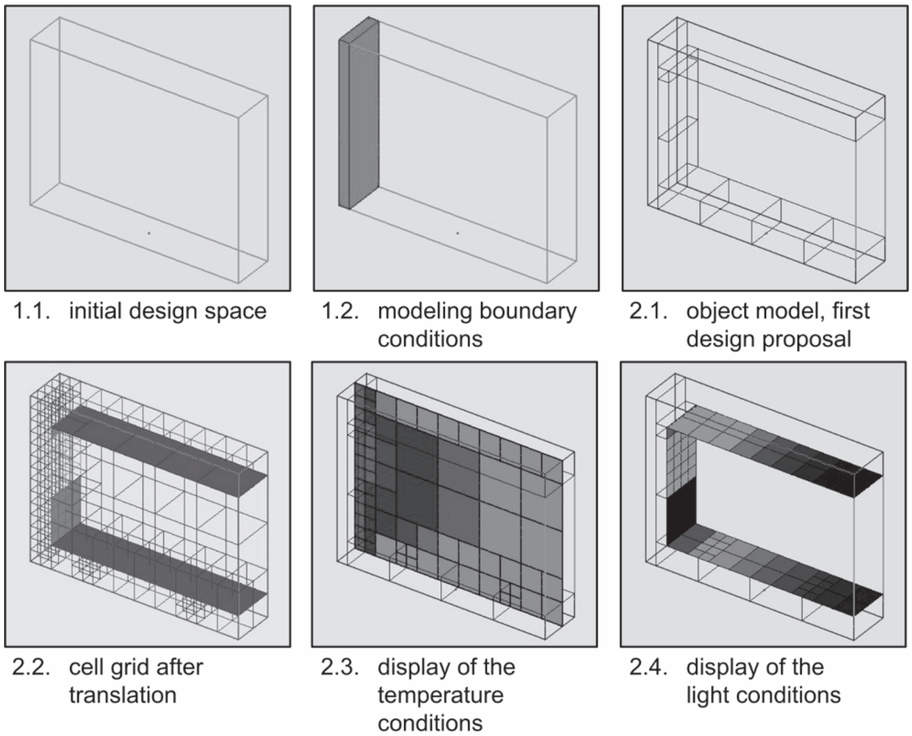


Figure 14. Sequence of steps in the Design Process.

The dark areas in the temperature display, which indicate uncomfortable hot conditions, around the heating element and the light fittings suggest that lower temperatures and control functions for the heating system and the lights are required to prevent the room from over-heating. Further steps of design improvement would follow.

5. Restrictions and Observed Problems

The prototype, as implemented, is currently not applicable in a real world design process. This is due to long processing times for the model translation and the simulation itself. Therefore a constructive dialog between the designer and the simulation tool cannot be established in the design development process.

Furthermore the attempts to implement the flow model, which would be essential for the assessment of comfort quality, were not successful at this stage and other physical models will require further refinement, adjustment and testing.

The size of the model is limited by memory constrains and the resulting translation and simulation time. Small cell sizes (<5cm) occasionally result in numerical problems during the simulation. Due to the cubic form of the cells a large number of cells and cell faces is generated when models with thin objects (e.g. table tops) are translated. This results in a larger of conjunctions, especially remote-conjunctions, and causes memory problems and long translation and simulation times without adding much accuracy to the simulation results.

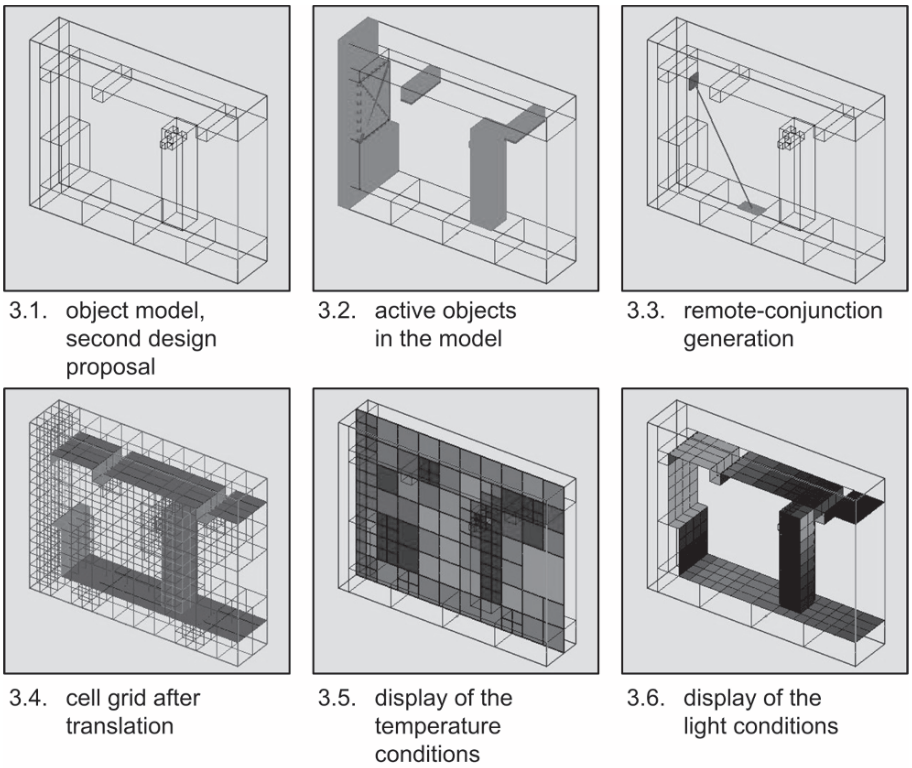


Figure 15. Sequence of steps in the Design Process.

For simplification and robustness of the implementation of the model translation algorithm only rectangular objects with sides parallel to the cell grid can be used for modeling. Nevertheless the concept of the cells and the cells faces would allow the representation of objects with non-rectangular shapes. The accuracy of the translation of such objects would be improved with reduced cell sizes (similar to higher accuracy of pixel graphics with smaller pixel sizes).

Although various problems and limitations exist, the research demonstrates the separate steps in the process and the application of the sequence of steps in the design process successfully. Furthermore the implemented system shows a way towards highly integrated simulation of physical processes in the digital world.

6. Conclusion

A space-based model to simulate and to display highly integrated physical phenomena on basis of digital object-oriented design representations, which only contain geometry and basic geometry-related property information, is described and demonstrated briefly. Its potential application in the performance-based design process is presented and its current stage of development is discussed.

It must be mentioned that the presented prototype was not developed to be applicable in a real world design process, that technological constrains prevent the modeling of larger model sizes and that the physical model requires further development, refinement and testing, before the system is applicable to predict physical behavior in a useful manner. Nevertheless it was demonstrated how the system would be applicable to bridge complexity of the analysis activity in the digital design process.

Although the focus of this paper is the augmentation of design representations to enable performance-centered designing, further applications could be imagined. For example the concept could be used in physically realistic virtual environments to enable research on overall comfort or research on adaptive comfort models with human-like agents in virtual environments in future.

Acknowledgements

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References

ESRU: 2002, *The ESP-r System for Building Energy Simulation - ESRU Manual U02/1*, University of Strathclyde, Glasgow.

Fredkin, E: 1992, Finite nature, Available Online: http://www.digitalphilosophy.org/download_documents/finite_nature.pdf

Gero, JS: 1990, Design prototypes: A knowledge representation schema for design, *AI Magazine* **11**(4): 26-36.

Künzel, HM: 1994, Verfahren zur ein- und zweidimensionalen Berechnung des gekoppelten Wärme- und Feuchteverhaltens *Bauteilen mit einfachen Kennwerten*. Fakultät Bauingenieur- und Vermessungswesen der Universität Stuttgart, Lehrstuhl Konstruktive Bauphysik. Stuttgart, Universität Stuttgart, Germany.

Mahdavi, A: 1999, A comprehensive computational environment for performance based reasoning in building design and evaluation, *Automation in Construction* **8**: 427-435.

Marsh, AJ: 1997, *Performance Analysis and Conceptual Design*, PhD Thesis, School of Architecture and Fine Arts. Sydney, University of Western Australia.

Schwede, DA: 2006, *Towards a Universal and Integrated Digital Representation of Physical Phenomena*, PhD Thesis, Faculty of Architecture, University of Sydney.

Suter, G and Mahdavi, A: 2003, Aspects of a representation framework for performance-based design, *IBPSA conference: Building Simulation 2003*, Eindhoven, Netherlands, Organizing Committee Building Simulation, pp. 1257-1265.

Vischer, J: 1989, *Environmental Quality in Offices*, New York, Van Nostrand Reinhold.

Zuse, K: 1970, *Calculating Space*, Cambridge, MIT Technical Translation of: Zuse, K. (1969) "Rechnender Raum", Schriften zur Datenverarbeitung, Vieweg&Sohn, Braunschweig; AZT-70-164_GEMIT, Massachusetts Institute of Technology.