MODEL-ADAPTIVE ANALYSIS OF INDOOR THERMAL COMFORT

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ABSTRACT

We address the model-adaptive coupling between computational codes for indoor thermal comfort analysis considering different levels of detail in space and time. Starting with a whole-year simulation, significant periods are interactively identified in terms of a coarse thermal comfort analysis. After refining these critical intervals with respect to the spatial resolution, a multi-segment manikin model interfacing with the human thermoregulation model of Fiala (Int J Biometeorol, 45:143–159, 2001) is applied for studying transient and local effects of thermal sensation. On a coarse level (pre-calculated view factors and heat transfer coefficients), parameters like the boundary conditions or the type of clothing can be modified online, results are updated in real time (computational steering). On a fine level, the thermoregulation model is linked with a geometry based zone model using a ray tracing method capturing the short wave radiation incident to the manikin surface and a radiosity solver for the longwave radiation. Ongoing developments concern a full coupling between the radiation solver and an interactive lattice Boltzmann type CFD solver by further enhancing the performance of the view factor computation.

INTRODUCTION

Building simulation is an inherent multi-scale and multi-level problem. The simulation scales range from milliseconds to years in time and from millimetres to kilometres in space. The various levels in simulation range from the environment and building surroundings over the point of view of individual building zones and the building fabric in terms of multi-layered structures up to the occupant's level considering user behaviour, temperature sensation and human thermoregulation (van Treeck 2009).

Concerning these different levels, the available physical resolution and computational resources, one distinguishes in building performance simulation between steady-state heat balances (coarse level), dynamic multi-zone models, and computational methods modelling fluid flow, radiation and heat conduction in detail (fine level). Coupled and integrated approaches exist in order to bridge the gap between the scales and levels.

The informative value of a thermal comfort analysis generally depends on the level of detail of the available simulation data. To capture the overheating risk within a building zone, for example, the frequency of occurrence must be known if operative room temperatures exceed a critical value in terms of a defined comfort zone (ASHRAE 2005, EN 15251 2007). For the analysis of radiation asymmetries, a geometric radiation model must be available in order to determine wall surface temperatures. In order to resolve for the local draught risk, a computational fluid dynamics (CFD) simulation is necessary for getting insight into the room airflow.

In practise, the empirical model of Fanger (1982) is frequently used as defined in the ISO 7730 (2005) and in the ASHRAE Standard 55 (2004). With known level of activity (in terms of metabolism) and clothing, the model considers the heat balance of the human body and statistically expresses the vote of people's satisfaction with the thermal environment to the ambient conditions using the PMV (predicted mean vote) or PPD (predicted percentage of dissatisfied) indices (Fanger 1982). The model is applicable to uniform and steady-state environments close to thermal neutrality. The cited ISO and ASHRAE standards also give tolerance limits for draught risk and asymmetric radiation, for example.

For naturally ventilated buildings, adaptive comfort guidelines (de Dear and Brager 2002) take into account behavioral and physiological adaptations of people and their expectation. The adaptations include changing clothing or opening a window, for example. In standards (ASHRAE-55 2004, EN 15251:2007, ISSO 2004), the comfort temperature is formulated in terms of the history of the outdoor temperature. Likewise, this method addresses the thermal state of the body as a whole. If combined with a long-term indicator, it is useful to predict the overheating risk in free running buildings.

The afore mentioned models are convenient for usual applications in building simulation but are not valid for local *non-uniform* or *transient* conditions as occurring in many situations of practical interest. Some publications recently address human responses under inhomogeneous and transient conditions at the same time (Zhang et al. 2004). Current research also focuses on the integration of detailed thermal manikin models (Huizenga et al. 2001, Fiala 2001, Tanabe 2002) into numerical simulation tools and their application in practise (Frijns et al. 2006, Kato et al. 2007, Nilsson et al. 2007, Niu et al. 2008, Paulke 2007, Streblow et al. 2008, Zhang & Yang 2008).

A thermal manikin model consists of a passive system taking physical and physiological properties and the blood circulation into consideration and an active regulation system (Stolwijk 1971) providing source terms for the passive model. With a thermal manikin, skin, surface and core temperatures become available. In order to correlate the obtained skin and surface temperatures with the user's comfort perception, further knowledge of the individually perceived *local thermal sensation votes* is required, i.e. a "comfort model". The ISO 14505-2 Standard (2004) establishes the experimental methodology.

Figure one exemplarily shows the link between equivalent temperatures (see ISO 14502-2 2004) and the acceptability for different body parts.

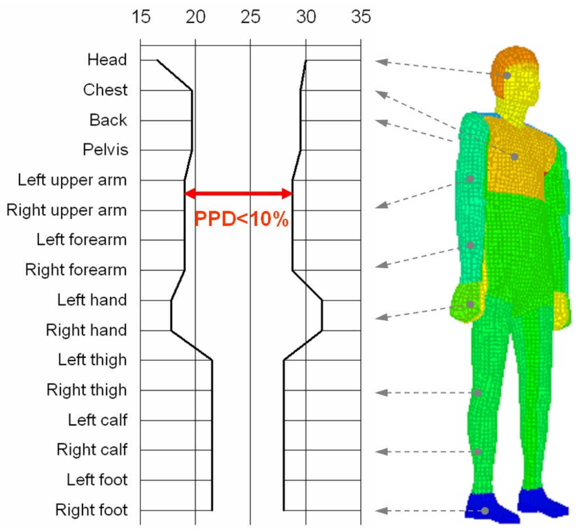

Figure 1: Comfort zone for various body parts (y-axis) drawn for 90% acceptability in terms of equivalent temperatures (x-axis). Redrawn from the values presented in (Bohm et al. 1990, Han et al. 2001) for a car cabin.

In order to compute the convective and radiative heat transfer between body and environment, either predefined heat transfer coefficients (Fiala 2001, de Dear et al. 1997) and view factors are required, or, better, a coupling with a flow and a thermal radiation solver must be achieved.

In this paper, we briefly outline the ongoing developments of an integrated tool for the model-adaptive coupling between computational codes for the indoor thermal comfort analysis considering the above-mentioned levels of detail in space and time. The tools involve a zone model, a human thermoregulation model, a refined zone model including a 2-band radiation solver and a lattice Boltzmann type CFD code. Where appropriate, the tool provides means of Computational Steering (van Liere et al. 1996), i.e. to interact with a running simulation online (not to be mixed with the term 'interactive visualization').

BASIC ZONE MODEL

For the tool on hand, a geometry-based multi-zone model has been developed and validated according to the VDI Standard 6020 recently.

Geometric model

For all kinds of simulations, a geometric model forms the basis for all subsequent computations. The model is represented by a boundary representation scheme (b-rep). Volumes and solids are modelled as hexahedral elements, i.e. the data structure of an element uses eight nodes and six surfaces, whereas surfaces are using four nodes. Openings in surfaces, such as for windows or doors, are modelled implicitly.

The air volume of a building zone consists of one or more fluid elements which are bounded by the structural elements. The outer shell of the air volume is explicitly available as surface model. This has considerable advantages: The air volume shell (including openings) is further decomposed into a set of facets for treating short- and long wave radiative heat transfer independently of the fluid domain discretization.

The geometric model contains attributes considering e.g. material properties or geometric boundary conditions, as well as member functions for determining the volume of a fluid element, the area of a window or the orientation of a surface, etc. The latter is necessary in order to query the surface type, i.e. belonging to a wall, a ceiling or a floor element.

Figure 2 depicts a part of the basic class model. In the class hierarchy, core classes are defined for the geometric model (GModel), the physical models (PModel), the material models (MModel), the zone model (ZModel) and the weather model (WModel).

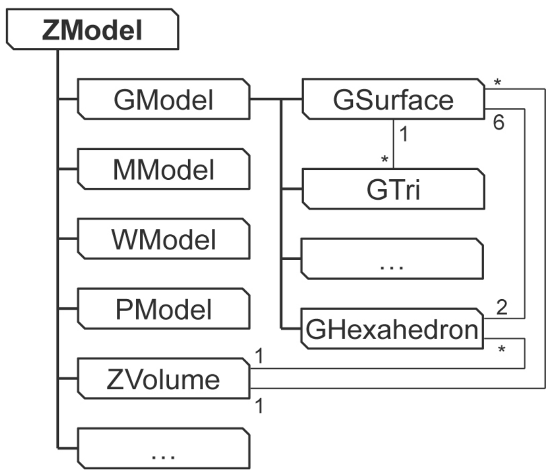

Figure 2: Extract of class structure of the iZone code. For the geometric model, the substructure is shown for the surface, tri and hexahedral elements.

Core functionality

The model makes use of an anisotropic finite volume conservation approach as suggested by Clarke (2001) where the physical problem is transformed into a set of conservation equations for energy, mass and momentum, which are then integrated at successive time-steps in response to ambient climate and control system influences. Energy balances involve short and long wave radiation processes, transient heat conduction through the structure and surface convection with empirical heat transfer coefficients (e.g. Alamdari & Hammond 1983). The heat flux through the structural elements (the wall assemblies) can for example be approximated in a one-dimensional form for each layer. Such a 1D-structural element is accordingly a specialized element which only has a single discretization direction.

For tracking the short wave radiation, a simplified ray-tracing algorithm is used; diffuse short and long wave radiation is treated via a radiosity method. The coupling between radiation solver and thermal network is explicit in order to improve the structure of the respective coefficient matrices and to use dedicated solvers each. The heating and cooling models are implemented as a convective source or sink term affecting the fluid element equation in order to maintain the fluid element at a defined temperature level.

Validation (VDI 6020)

The model has been subject to extensive convergence studies and validation calculations according to the VDI Standard 6020 (2001), a test suite for building performance simulation codes. The standard considers a single test room with e.g. heavy weight construction materials, which is adiabatically connected to other building parts and has one large glazed opening to the surroundings.

Example 1 of the VDI Standard analyses the behaviour due to solid heat conduction, independent of any type of radiation, whereas example 8 evaluates the short wave radiation, in this case independent of heat conduction (zero capacity). Example 13 combines all effects in a whole year simulation according to different boundary conditions.

For example, Figure 3 compares the plant output obtained by the iZone tool with other tools (negative value means cooling) for August 11 of TRY5 (sunny day) with the window of the test room oriented due South (benchmark 8 of VDI 6020). As requested by the benchmark definition, sun shading was applied over the whole year as soon as the radiation passed a threshold of 150 W/m².

Figure 4 details the performance of the heating plant [W] of the VDI test room for benchmark 13 of VDI 6020 in the period from January 31st to February 7th. The tool captures the dynamics and peak loads well. In Figure 5, the comparison of the maximum heating performances is printed. Occupants/equipment were working/operating during working days from 7:00 to 17:00. The plant was active from 8:00 to 18:00 on working days, otherwise a minimal base temperature (18°C) was maintained. For a detailed discussion of the whole test suite, it is referred to (van Treeck 2009).

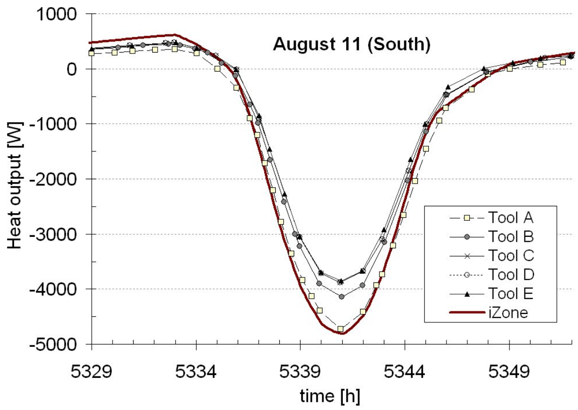

Figure 3: Comparison of the iZone plant output [W] with other tools for benchmark 8 of the VDI 6020

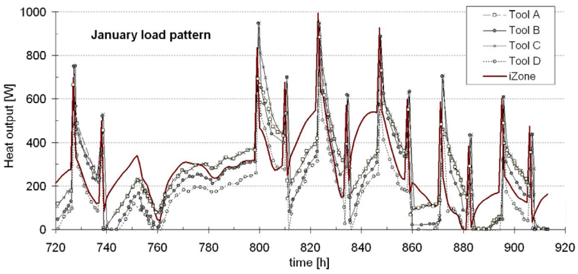

Figure 4: Heat output [W] for January load pattern obtained by iZone compared with other tools for benchmark 13 of the VDI 6020

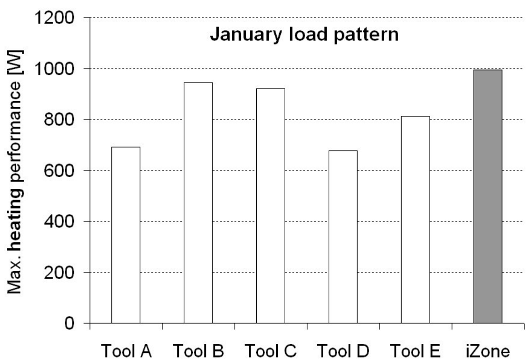

Figure 5: Comparison of the maximum heating performances for January (benchmark 13)

REFINED MODEL WITH MANIKIN

As the radiative heat transfer significantly contributes to the temperature distribution, the model makes use of a detailed window model and a ray tracing method for computing the short wave radiation. In case of the refined model, the geometry includes the facets of the thermal manikin surface as depicted in Figure 6. A radiosity method is applied for calculating the diffuse short- and longwave radiative heat exchange between room and manikin surfaces.

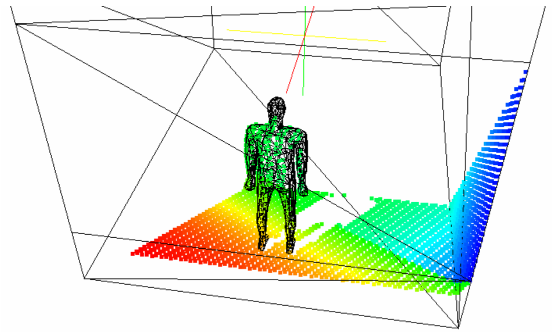

Figure 6: Ray tracing algorithm capturing short wave radiation incident to manikin surface

In order to reduce the effort of the view factor calculation, the contour and area integration scheme proposed by (Walton 2002) using the Gaussian quadrature is applied. Hierarchical space partitioning schemes or surface clustering techniques can further increase the performance of the visibility check.

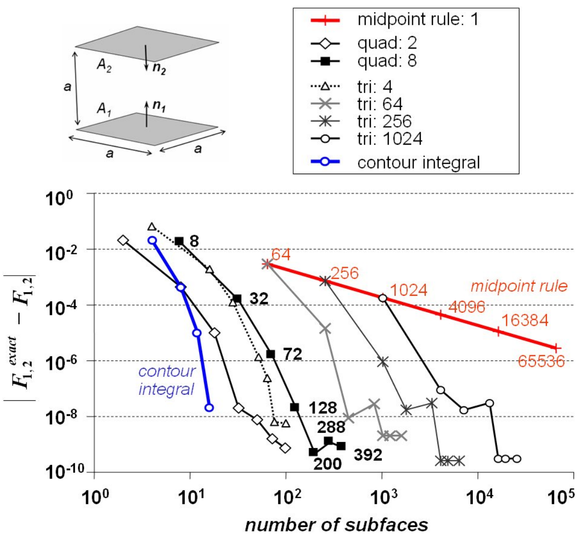

Figure 7: Convergence of view factor computation for different numerical integration methods

The effect of applying different numerical integration methods is displayed in Figure 7 for the case of the view factor calculation for two parallel finite surfaces. The x-axis thereby denotes the number of facets (the degrees-of-freedom) and the y-axis is the deviation from the (exact) analytical solution (obtained in this case by view factor algebra). The midpoint rule shows algebraic convergence (h-refinement) and is accompanied by extensive computing time (up to several hours for more than 10,000 facets). The contour (and area) integration with Gaussian quadrature converges exponentially and reduces the computational load by several orders of magnitude.

CONVECTIVE HEAT TRANSFER

For the convective heat transfer between manikin and surroundings currently predefined convective heat transfer coefficients are used (de Dear et al. 1997, Fiala 2001). The full coupling between the radiation solver and a lattice Boltzmann type CFD solver is subject to the current work. The interactive CFD model has previously been shown by the authors in (van Treeck et al. 2007 and 2008).

HUMAN THERMOREGULATION AND TEMPERATURE SENSATION

The thermal sensation and thus the comfort perception depends on the overall thermal state of the body with weighted influence of the individual body parts (Zhang et al. 2004). Local thermal sensation votes (LTSV) of individuals can be experimentally correlated to equivalent temperatures (TEQ) as described in ISO 14505-2 (2004). A regression analysis usually leads to a linear relationship $LTSV = f_i(TEQ)$ for each body segment i.

If these empirical relationships are known, the results obtained with a computational thermal manikin can be correlated to the local thermal sensation, and visualized on the "artificial skin" of the dummy. With a thermal manikin, resultant surface or skin temperatures can be obtained which need transformation into equivalent temperatures. Figure 8 exemplarily shows the link between both quantities. For a full picture of the methodology it is referred to the article (van Treeck et al. 2009).

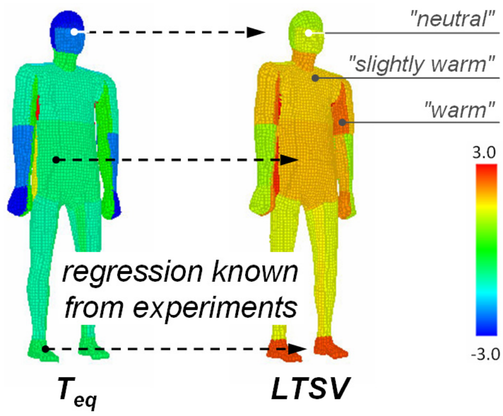

Figure 8: Visualization of local thermal sensation votes on the artificial skin of the manikin using a NASTRAN type geometry. The correlations between T_{eq} and LTSV are found by experiments (van Treeck & Frisch et al. 2009)

The human body is able to maintain its core temperature at a constant level for a wide range of ambient conditions as the thermoregulation system controls the thermal state in terms of shivering, sweating, and peripheral vasomotion (Stolwijk 1971).

These reactions of the central nervous system are an answer of multiple functions of signals from core and peripherals and can be correlated with the skin and core temperatures and their variation over time in a thermoregulation model (Stolwijk 1971, Fiala 2001).

Next to an active thermoregulation system, a thermal manikin model consists of a passive system modeling the heat exchange between body and environment and the heat transfer within the tissue including the blood circulation. Besides two-node models (Gagge, 1973), multi-segment models are known which are founded on the early work of Stolwijk (1971), for example (Huizenga et al. 2001, Fiala et al. 2001, Tanabe et al. 2002, or Wissler 1985). Most models use a decomposition of the human body into segments and a further partition into concentric layers.

PARAMETRIC MANIKIN MODEL

In order to interact with the refined zone model, an object-oriented, parametric multi-segment manikin model has been developed. The model allows for motion control by transforming body parts with an armature model based on the H-ANIM (2008) Standard. It relates the topological dependencies between the "bones" as shown in Figure 9. Joints between segments are modeled by intersecting half spherical elements (Yue 2008).

The segmentation is chosen in accordance with the human thermoregulation model proposed by Fiala (2001). Body segments are further decomposed into anterior, inferior and posterior parts. Several facetted geometric models are available such as the MSIS Standard (NASA 1995) for the parametric model or other predefined (fixed) NASTRAN geometries. The LS-PrePost (2008) meshing software has created the facetted sub models (Yue 2008).

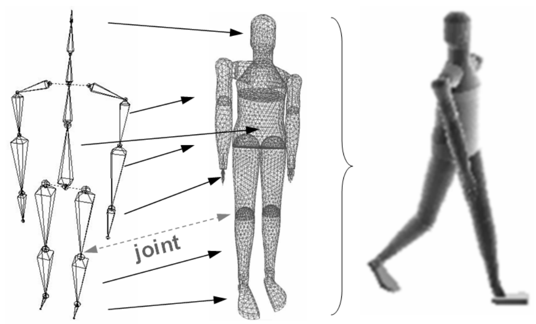

Figure 9: Armature model, facetted submodels and transformed parametric manikin model (Yue 2008)

The facetted surface model is used for the view factor computation (a further coarsening algorithm is applied). It also serves as input for a CFD solver which is not subject to this paper. The computed quantities are visualized on the "skin" of the virtual manikin such as skin or surface temperatures or local thermal sensation votes.

The parametric model interfaces with the FIALA-FE (2008) core implementation (Paulke 2007) of the thermoregulation model proposed by Fiala (2001) within the FEM software package THESEUS-FE (2008). The discretization with spherical and cylindrical elements is similar to the original model but makes use of a finite element approach in order to represent the concentric layer structure of the manikin for solving the bioheat equation (Pennes 1948). The solver is used in a non-coupled mode, i.e. the internal FIALA-FE core model is used without interfering with the built-in geometric model (Frisch 2008).

COUPLING INTERFACE

The software interface shown in Figure 10 controls the communication between the FIALA-FE solver and the zone/CFD models (van Treeck & Frisch 2009). The FE solver is script-controlled in terms of starting, stopping and resuming a simulation. Therefore, the interface makes use of the ASCII file interface provided by THESEUS-FE (2008). The coupling is explicit and provides a variable time step size where the postprocessing interval is independent from the adaptive solver step size.

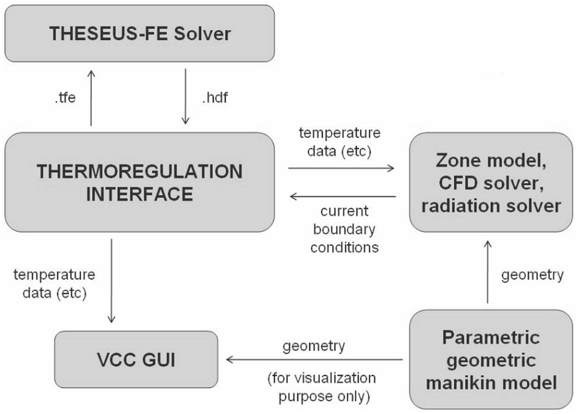

Figure 10: Coupling strategy between THESEUS-FE, the thermoregulation interface with GUI and other computational codes (Frisch 2008)

The interface can be operated in two modes:

In the *stand alone/direct mode*, the application forms a *"virtual climate chamber"* providing a graphical user interface for user interaction. In this case, the manikin is placed in a rectangular box where predefined heat transfer coefficients and view factors are used in order to compute the heat exchange between body and environment. The user can online modify the manikin position (upright, seated), the type of clothing (summer, winter, none), the activity level and the thermal boundary conditions *during the simulation* (Frisch 2008).

In the *coupled mode*, the GUI acts as a *"vital function monitor"* computing and displaying the thermal state of the manikin. API functions allow for bi-directionally transferring boundary conditions and manikin related information between the solvers.

Depending on the selected level of detail (coarse/ refined zone model), the manikin is applied in the above described way using predefined heat transfer coefficients and view factors, or by individually computing the short- and long wave radiative heat transfer with the predefined geometric facet model. The coarse approach is feasible in real-time where the thermal multi-zone model provides mean air temperatures and temperature values of the surrounding room surfaces. A reasonable (real) time interval for an interactive analysis is *O(min...h)*. The refined model implies more computational costs and can be applied for resolving *O(sec...min)* for simplified geometries.

SIMULATION

Pre-simulation at coarse level

In order to identify periods where thermal comfort conditions are not satisfied in a building zone, a whole-year simulation is initially performed with the described standard zone model.

The initial simulation provides room and surface temperatures etc. on an hourly basis (or less) as input for the first, coarse comfort analysis. Having selected such a critical section, the time resolution is refined and results are updated by automatically restarting the simulation with known solution vector at the beginning of the respective interval. Figure 11 details this idea of "zooming" into a simulation for the case of a single building zone.

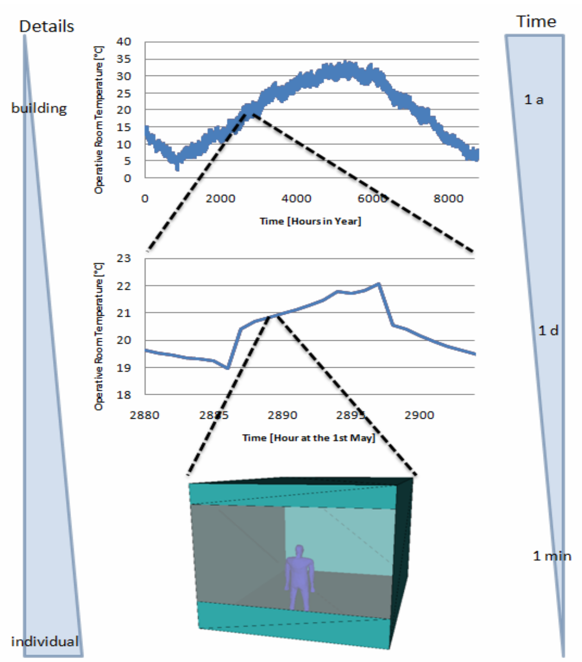

Figure 11: Level of detail dependent analysis

For the coarse analysis, the acceptable ranges of temperatures can be determined in terms of the static or adaptive comfort envelopes as defined in the standards (ASHRAE 55-2004, ISO 7730:2005) or (ASHRAE 55-2004, ISSO 74:2004, EN 15251 2007), respectively.

For example, in Figure 12 the operative room temperatures are plotted against the exponentially weighted running mean outdoor temperatures for the adaptive comfort envelope of the EN 15251:2007. The calender type view in Figure 12 indicates the deviation (in [K]) of the daily maximum operative temperatures from the upper part of category II. The latter is suggested as a descriptive method for identifying (and locating) significant periods where comfort criteria are violated.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0.041	0.51	0.466	0	0	0
2	0	0	0	0	0	0	0	0	0.912	0	0	0
3	0	0	0	0	0	0	0	0	0.061	0	0	0
4	0	0	0	0	0	0	0	0	0.525	0	0	0
5	0	0	0	0	0	0	0	0.1	0	0	0	0
6	0	0	0	0	0	0	0	0.212	0	0	0	0
7	0	0	0	0	0	0	0	1.518	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0.218	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0.684	0	0	0	0
12	0	0	0	0	0	0	0	0.699	0.6	0	0	0
13	0	0	0	0	0	0	0	0.188	0	0	0	0
14	0	0	0	0	0	0	0.734	0.574	0	0	0	0
15	0	0	0	0	0	0	0.236	0.306	0	0	0	0
16	0	0	0	0	0	0	0.125	0	0	0	0	0
17	0	0	0	0	0	0	0.408	0	0	0	0	0
18	0	0	0	0	0	0	0.643	0	0	0	0	0
19	0	0	0	0	0	0.007	0	0.409	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0.224	0	0	0	0	0
22	0	0	0	0	0	0	0.233	0	0	0	0	0
23	0	0	0	0	0	0	0.605	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0.046	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0.185	0	0	0	0	0
29	0		0	0	0	0	0.31	0	0	0	0	0
30	0		0	0	0	0	0.327	0	0	0	0	0
31	0		0		0		0.794	0		0		0

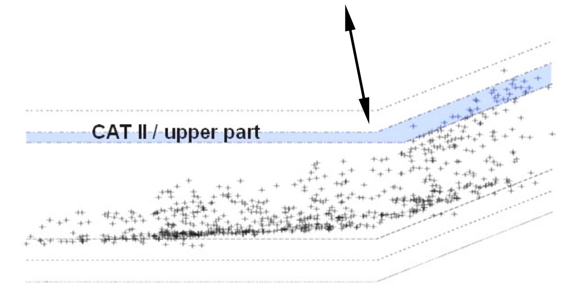

Figure 12: Postprocessing of simulation data using the adaptive comfort envelope EN 15251:2007 and a calender type view (columns=months, rows=days).

Integrated comfort analysis

Having identified such a critical period, results of the selected time step are transferred to the "virtual climate chamber", where the simulation is resumed using the thermal manikin for a local analysis.

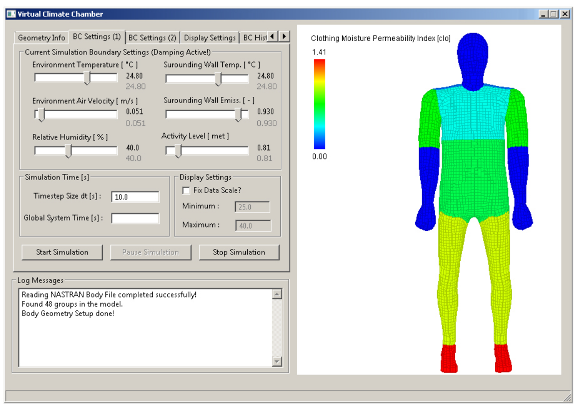

Figure 13: GUI of the thermoregulation interface

The graphical user interface (GUI) shown in Figure 13 represents some kind of ”vital function monitor” displaying skin temperatures or local thermal sensation votes (see Figure 8). For details it is referred to (van Treeck & Frisch et al. 2009). The figure illustrates the change of the different quantities over time – here in terms of the surface temperature variations according to modified boundary conditions and clothing parameter. The two boxes in the right hand frame of Figure 13 display user selected scalar quantities over time such as the hypothalamus temperature, the predicted mean vote (ISO 7730) or the dynamic thermal sensation index (Fiala 2001).

Current work: CFD integration

With a CFD model in turn, the flow regime in the vicinity of the body can be resolved at a higher resolution. The complexity of mesh generation, the physical resolution and thus the computational costs thereby restrict the application of CFD in real time.

The authors in (van Treeck et al. 2007, 2008) and (Wenisch 2007) have previously showed the principle of steering a flow simulation using a lattice Boltzmann type CFD solver developed at the Technische Universität München. Figure 14 gives an example of interactively steering a flow simulation with our code at a holobench device installed at the Leibniz Computing Centre (Garching, Germany).

In the case shown in (van Treeck et al. 2008), the parametric manikin model is controlled by the steering environment which consists of a parallel CFD kernel and an integrated VR visualization component. The full coupling of the radiation solvers with the CFD code is subject to current research activities.

Further work also addresses the developments of hierarchical space partitioning schemes for the visibility check and surface clustering techniques for increasing the performance of the radiation solver.

Figure 14: Computational steering means interacting with an ongoing (e.g. CFD) simulation, for example using a holobench with space pointing device (picture courtesy of TUM and LRZ, Germany)

CONCLUSION

In this paper, we have presented a methodology for coupling computational codes for indoor thermal comfort analysis in a model-adaptive way considering different levels of detail in space and time. A parametric multi-segment manikin model interfacing with the FIALA-FE implementation of the human thermoregulation model of Fiala et al. (2001) has been developed. The 3D visualization on the artificial skin of the manikin includes the skin and hypothalamus temperatures; for the body PMV, PPD, DTS, and other quantities are output.

Although getting insight into local effects and hot spots, a drawback of the model is, however, that it does not (yet) consider the accumulation of heat stress events. Robinson and Haldi (2008) for example discuss the latter topic.

Ongoing developments concern a coupling between the radiation solvers and an interactive lattice Boltzmann type CFD solver as well as increasing the performance of the two radiation solvers.

Interactive simulation – in the opinion of the authors a main resource in the daily engineering work of tomorrow – will always be a trade-off between accuracy and computational costs. Therefore, a model-adaptive choice of algorithms and solvers makes sense in terms of the physically required and computationally affordable spatio-temporal resolution.

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