WILL EQUATION-BASED BUILDING SIMULATION MAKE IT?

EXPERIENCES FROM THE INTRODUCTION OF IDA INDOOR CLIMATE AND ENERGY

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ABSTRACT

In building simulation, as in several other domains, traditional monolithic simulation codes are still in dominance over simulators based on symbolic equations in a general modeling language. Introduced in 1998, IDA Indoor Climate and Energy has become the first widely spread thermal building performance simulator based on the new technology. Developing a full-fledged dynamic whole-building simulation program is a formidable endeavor in any setting and since the first beta version in 1997 a number of lessons have been learned. The paper shares some of these experiences concerning general program structure and GUI design as well as issues specifically linked to equation-based modeling using a variable timestep differential-algebraic (DAE) solver.

INTRODUCTION

Most will agree that building simulation is likely to play an increasingly important role in the future. Roughly half of the world's energy consumption and associated CO_2 production is attributable to buildings. Computers are steadily becoming more performant, as are new generations of their human operators. Consequently, from the mid eighties through the mid nineties, several projects were initiated to formulate requirements for and conduct preliminary research on so called "next-generation" building simulators [Clarke et al. 1985; Sowell et al. 1986; Bonin et al. 1989; Clarke and MacRandall 1993; Crawley et al. 1997; see also Gough 1999 for an overview]. A fairly broad consensus was reached around some issues:

- The existing simulators were too rigid in their structure to be able to accommodate the improvements and flexibility that would be called for in the future. Each added feature required a larger implementation effort than the previous one. Complexity was getting overwhelming, making improvements difficult also for the original developers.
- A promising technology for the future were the general simulation methods offered by equation based methods using program-neutral model descriptions and domain-independent solution methods.

Although nothing really has happened in recent years to change the fundamental reasoning, a more defensive attitude has grown to prevail within the building simulation community. Several factors seem to contribute:

- some exploratory projects did not deliver as expected
- leading research groups have reverted back to existing solutions and "organic" evolution
- multi-domain simulation is being attempted by coupling of existing domain specific simulators (co-simulation)
- driven by product model research, attention has shifted from new tool development to improved integration of existing tools into the design process

The IDA project, initiated at the Swedish Institute of Applied Mathematics in the late eighties, is one of a few efforts that have been pursued beyond the stage of prototyping. In 1995, a broad Scandinavian industrial consortium was formed to exploit the developed general simulation technology within the AEC industry. The main result of this effort was IDA Indoor Climate and Energy (ICE), the first version of which was released in May 1998.

After a few years on the market, it is now possible to summarize. The paper discusses broad issues of building simulation in the context of specific design decisions made in IDA and IDA ICE. In the next section, a brief characterization of the building simulation market is attempted and the current coverage and penetration of IDA ICE is presented. After that, the situation on the DAE based simulation arena is briefly analyzed, followed by a presentation of main features of the physical models in IDA ICE. In the fourth section, some numerical performance comparisons with a tool of the traditional design (EnergyPlus) are made. These are followed by a discussion of needed DAE environment facilities for end-user simulator distribution. Two remaining important issues are briefly mentioned in the last sections, IFC (Industrial Foundation Classes) and CFD.

SCOPE OF IDA ICE

While the technical challenges of simulating a building in sufficient detail are formidable, technology transfer issues still define the practical limits of the field. There is an enormous gap between state-of-the-art development and the everyday practice that must be dealt with from a commercial software perspective. In this context, it may be useful to characterize the scope and fragmentation of the building simulation "market." While recognizing the importance of multiple related simulation domains, such as light, acoustics, structural analysis etc., we will concentrate here on building performance simulation (BPS) for thermal processes.

The target domain of various thermal simulation tools can be characterized as a multi-dimensional space of (at least) the following dimensions (Table 1):

Table 1 Market segments for thermal BPS

dimension	*segmentation*
User:	Home owner; Professional owner; Building services contractor; Architect; Stnd HVAC consultant; Advanced HVAC consultant; Mainstream research; Advanced research
Time resolution:	Static; Monthly, Design day; Hourly; Controller time scale
Physical extent:	Single component; Single subsystem or zone; Multi-system, multi-zone
Engineering culture:	Essentially a subdivision by country

Assuming roughly 25 different engineering cultures around the industrialized world, this subdivision leads to some 8x5x3x25 = 3000 different segments. Together, these form a substantial market, but few single segments are significant enough today for commercial exploitation, as can readily be witnessed by the modest number of non-government-financed organizations in the field. Most technology providers and active user communities operate in a single segment, such as for example: advanced HVAC consultants, running a multi-zone, hourly tool in the US or, similarly, in the UK.

Tailoring a tool and associated services to the target segment(s) is essential. Users expect no less from a BPS tool than from other software such as CAD tools, with a significantly larger local market. In current practice, most efforts to meet the needs of a segment are vertical; relying only on general, low-level tools such as compilers, everything needed to satisfy a segment is developed by the same group.

Since the inception of the IDA project, the ambition has been to develop a simulation infrastructure capable of serving a large number of segments. The resulting IDA Simulation Environment is in fact not limited to building simulation but forms the base of industrial applications in multiple domains such as rail and road tunnel ventilation, fire modeling, separation plant modeling, automatic refuse collection systems etc.

From the developer's perspective, the advantages of relying on a general simulation framework are significant, allowing the sharing of many resources between segments. The most obvious elements of such an infra structure are model languages, model libraries and solvers, but there are in fact several others such as tools for data bases; time series; user interface construction; CAD support; multi language support; optimization; input/output management, presentation and export; data mapping; scripting languages; web services etc. Users also benefit from coherence among related segments, allowing seamless mobility over segment boundaries.

IDA ICE is presented via three different user interface levels: Wizard, Standard and Advanced. The Wizard level is intended for less experienced users with particular focus on a certain type of study. The Standard level corresponds roughly to the graphical user interface (GUI) of a typical 3D graphical multi-zone BPS tool, requiring the building designer to formulate a meaningful simulation model in terms of thermal zoning etc. In the Advanced level, the user is allowed to directly interact with the mathematical model in a way that is not offered by traditional tools. Currently, a single wizard level interface called IDA Room is predominant. It is shipped as part of the standard product, but is also available free of charge as an Internet application. In the future, several additional wizard level interfaces are planned for various segments. Please visit www.equa.se/ice for some video and graphical illustrations of the ICE GUI. Table 2 depicts the current penetration and scope of the three ICE interfaces among market segments previously defined.

Table 2 Current ICE penetration and scope.

User interface:	IDA Room wizard	ICE Standard Level	ICE Adv. Level+NMF
# users:	1600	400	100
User:	Building services contractor; Architect; Stnd HVAC consultant	Stnd HVAC consultant - thru- Advanced research	Adv. HVAC consultant - thru- Adv. research
Time resolution:	Design day	Design day; Hourly; Controller time scale	Design day; Hourly; Controller time scale
Physical extent:	Single subsystem or zone;	Single sub-sys. or zone; Multi-sys., multi-zone	All
Engineering culture:	Sweden; Finland; Poland; Germany; Switzerland; France; UK	Sweden; Finland; Germany; Switzerland; UK	Sweden; Finland; Norway; Germany; Switzerland

The structure of IDA ICE is ideally suited for customization, also for individual design projects. Table 3 summarizes some major customized versions that are permanently maintained.

Table 3 A selection of IDA ICE customizations

Termodeck	Wizard level interface, NMF models and Standard level GUI objects for design of Termodeck buildings with ventilated hollow core slabs.
Danfoss	NMF library and Advanced level GUI objects for detailed studies of hydronic climatization systems.
Are Sensus	NMF library and Advanced level GUI objects for designs based on the Finnish innovative office HVAC system.
IDA Kachel	An Internet based design tool for wood stove heating in Austria and Switzerland.

DAE BASED BUILDING SIMULATION

Any designer of a building simulator must first of all find or construct some framework in which to express the physical models to be implemented. A great majority of existing tools and also some recent projects such as EnergyPlus, rely on a domain dependent infrastructure which is formulated in the early stages of the project to accommodate the models envisioned at this stage. As for any design project, early decisions will have tremendous impact on the rest of the work throughout the lifecycle. The designers of TRNSYS, for example, in the early seventies, had a great vision and constructed a simple, yet expressive "world" which has served the building simulation community well for soon thirty years.

When deciding on a basic framework, one should ask what the truly domain specific features of the target area are so these can be fully exploited in the tool. Voltage and current are for example important for an analog electronics simulator and early building simulation efforts were often rooted in clever methods to predict heat propagation through walls. We think the TRNSYS designers in the seventies realized something fundamental about buildings and their service systems; it is virtually impossible to formulate anything reasonably strict and truly domain specific about a building simulation. Consequently, the TRNSYS design could have blossomed in any of several fields. An awesome mixture of various models are needed for state-of-the-art building simulation. Fortunately, the situation is similarly disordered in many other domains such as chemical process plant, whole-vehicle, mechatronic and aeronautical simulation. True multi-domain approaches are needed.

Also for a general class of problems such as lumped parameter models of piecewise continuous modular dynamical systems, there is a range of expression paradigms to choose between such as Bond Graphs (20-Sim, MS1) block diagrams (Simulink, VisSim), subroutines or classes with specified interfaces (TRNSYS, HVACSIM+) or symbolic differential-algebraic equations (DAEs) (as in IDA, Dymola, SPARK, SMILE, ALLAN.Simulation and CLIM 2000-ESACAP). With the possible exception of Bond Graphs, serious efforts at modeling buildings have been made with all of the mentioned tools [Felgner et al. 2002, Musy et al. 2001, Nytsch-Geusen and Bartsch 2001; Jeandel et al. 1997; Murphy and Deque 1997]. In recent years, MATLAB-Simulink has grown to almost a de-facto standard in non-CFD scientific computation. However, closer inspection of building simulation models made with the listed tools will reveal that Simulink models are orders of magnitude smaller (or slower) than those made with more powerful tools. The current version of Simulink is not likely to be able to contend with the state-of-the-art efforts.

The new and ambitious modeling language Modelica (www.modelica.org), has shown potential to bring order to the fragmented world of DAE based simulation. It draws on the collective experience of a large number of first-generation languages and since the first tool (Dynasim 2001) appeared in 1999, several large industries such as Toyota, Ford, United Technologies, Caterpillar, ABB, Alstom, TetraPak etc. have adopted it. Impressive Modelica models have been reported at two well-attended international Modelica conferences. In the automotive industry, multi-domain, whole-car simulators of previously unprecedented size and complexity have been developed [Tiller et al. 2000; Bowles 2001].

The IDA team has been active in DAE language design since the late eighties when the Neutral Model Format (NMF) was first proposed to ASHRAE and the building simulation community [Sahlin and Sowell 1989]. In addition to several prototypes for various target environments, quality translators have been developed for IDA, TRNSYS and HVACSIM+ [Sahlin 1996]. The first version of the public domain model library of IDA ICE was developed in NMF within IEA Task 22 [Bring et al. 1999].

NMF was designed to bring the power of DAE based modeling to the building simulation community and yet be compatible with major building simulators such as TRNSYS, IDA and SPARK [Sowell et al. 2001]. From a technology point of view, this effort has been a success but the language has never caught the sustained interest of independent building simulation developers.

The IDA team has been part of the Modelica development effort since the first design meeting in 1996. During this time several prototypes have been developed for the successively evolving Modelica specification. Now, with Modelica 2.0, the language is sufficiently stable and the first full-complexity Modelica application (subway traffic, ventilation and fire) for IDA Simulation Environment was developed during the spring of 2003. The next major release of IDA ICE will provide Modelica support and it is envisioned that most future major library development efforts around IDA ICE will be Modelica based.

However, NMF will also be supported for the foreseeable future, since the straightforward language structure and lower cost of tools is better suited to many less frequent modelers. An automatic translator from NMF to Modelica has been developed.

THE IDA ICE MODEL LIBRARY

The basic design principle behind the IDA ICE library has been to provide the best possible resolution of key phenomena while enabling whole-building, full-year simulation within commercially acceptable execution times. The first version of the library was developed with in IEA Task 22. Admittedly, in the first version of the simulator in 1998, whole-building simulation was reserved for those with sufficient patience. However, with current IDA numerical methods on today's hardware, the library is more appropriately placed. We will briefly outline the phenomena modeled (and not yet modeled) with special emphasis on features that are unusual in a whole-building simulator context.

Flow networks. Pressure is modeled throughout air and water flow networks. For air this means that stack and wind driven flows are consistently modeled as in air flow network programs such as COMIS. For mechanical circuits, ideal flow controllers are often used to maintain a given flow in order to avoid the need to input accurate pressure drop data. CO_2 and moisture are modeled for all air streams. High on the development agenda are models for large horizontal openings.

Control principles and dynamics. Most control loops are explicitly modeled using separated P or PI controllers. Variables such as massflows, temperatures and pressures are never regarded as given, but are always computed, often via more or less idealized control loops. To compute, e.g., a cooling load, some large but finite capacity room unit and associated sensor and controller are always used. Fast local loop dynamics are often not modeled in the basic library in the interest of calculation time. However, to study fast timescales in some part of the system, sensor, actuator and relevant process dynamics may be modeled for the local loop. This possibility of modeling local circuits to an arbitrary level of time resolution in the context of a whole-building model we believe to be unique. It has for example been used by Danfoss to study consequences of details such as valve hysteresis on whole-year energy and comfort. It is planned to implement simulation of more complex control systems described with the IEC 61131-3 standard. This will enable off-line programming and testing of building control systems.

Long-wave radiation. Full non-linear Stefan-Boltzman long-wave radiation is modeled for shoebox zones only. An MRT approach is presently used for zones with more complex geometry. View factors for arbitrary obstructed surfaces will be included.

Short-wave radiation. ASHRAE (default), Kondratjev and Perez sky models are available. External shading is calculated for direct and diffuse light for arbitrary four cornered flat opaque surfaces. Shade presence may be controlled. Semi-transparent surfaces will be implemented. Inside the zone, incoming short-wave is distributed diffusely according to view factors. Internal windows are currently not implemented but are high on the wish list. A special object for five-surface skylights enable modeling of complex roof shapes. For these, multiple beam reflections is modeled.

Convection (Film coefficients). An empirical non-linear model for internal film coefficients depending on surface slope and temperature difference is used. Anther fit is used for wind dependence of external film coefficients.

Solid heat transfer and thermal storage. The default wall is a finite difference model with automatically suggested, non-uniform grid spacing. It uses a special integration technique to fully utilize matrix structure. A variant of the same model without native integration is also available. In addition, an automatically optimized reduced RC-network model is available (default in v. 2.11). Ground heat transfer is currently normally modeled as two 1D heat transfer paths, one to the surface and one to a fixed ground temperature. A uniform grid 3D model is available separately in NMF but a comprehensive ground model which is directly accessible from the Standard level is needed. See also the discussion below on the Femlab link.

Other zone model features. Fanger's models (ISO 7730) for comfort and occupant loads are used, enabling calculation of PPD in multiple zone locations and alleviating the user from having to estimate occupant loads. A simple model (Mundt 1996) for linear vertical temperature gradients is frequently used. However, more sophisticated gradient models are desired. Room units in IDA ICE are based on manufacturer's data. Radiative/convective split is calculated based on computed surface temperatures and exposed surface area.

Secondary systems. The models from the ASHRAE secondary toolkit have been translated into NMF and complemented with variants using fewer and capacity-independent parameters and with built-in control loops. Models that are suitable for whole-year simulation are currently missing for dry and desicant wheel heat exchangers.

Primary systems. Currently, only a simple boiler and chiller are available with given COP and limited capacity. This is an area in which IDA offers good opportunities for integrating models that are currently unavailable in a whole-building context.

The model library is in the public domain and is shipped with IDA ICE as NMF source code. Many users adapt and complement the library to suit their needs. In fact, the main motivation behind DAE based modeling is to provide a radically improved environment for developing, maintaining and enhancing a large set of physical models.

Some questions that should be considered in the evaluation of different approaches are:

- How long does it take for a beginner to add a new model?
- How efficient is the model development and testing process?
- What degree of model reuse is possible?
- How well can separate developers benefit from each other's work?

Unfortunately, reports from unbiased users with experience from more than a single development environment are rare. A listing and discussion of pros and cons of DAE approaches can be found in [Sahlin 2000].

NUMERICAL PERFORMANCE

In the discussion of future building simulation software, superior numerical performance is the main argument for advocates of the traditional design with problem-specific solution methods and model formats [Clarke 1999]. It seems natural that taking full advantage of the structure and timescale of the problem at hand will result in more efficient code. However, what is generally *not* utilized in traditional simulator design are the powerful general solution methods, e.g. sparse solvers, that have been developed by professionals in scientific computing over the last few years. It is difficult to make fair comparisons of various approaches. A comprehensive effort should address at least the following issues:

- Physical phenomena modeled
- Level of ambition of the physical models
- Level of numerical accuracy obtained in each timestep
- Time resolution obtained

The creation of a practical and politically acceptable framework for fair comparisons of numerical performance is beyond the scope of this paper. However, such a performance test suite and procedure (in the BESTEST) style would be welcomed and it should be of great help in the appraisal of new and inventive simulation methods.

In order to give some sense of the performance of a DAE based tool such as IDA ICE in comparison with a modern tool in the traditional design tradition, some rough comparisons between IDA ICE (v. 3.0 build 11) and EnergyPlus (v. 1.0.3.019) have been made. The two tools differ significantly in fundamental models used and only a modest effort has been devoted to creating equivalent cases in the two tools. The numbers given should not be over-interpreted.

A major difference between everyday IDA ICE modeling and that of most other tools is that virtually all IDA ICE models have air flow network features modeled. Various air flow apertures with wind and stack driven flows are naturally added by most modelers, given appropriate user interface support. (After all most doors remain open in a building). We have therefore chosen a three zone case with natural ventilation from the EnergyPlus suite of samples (3zvent). In the original version, the EnergyPlus model was equipped with temperature and enthalpy based window opening control schemes. However, these showed time-step dependent oscillations in EnergyPlus and the controls where therefore disabled by providing extreme setpoints, effectively opening both windows once for one hour per day.

An IDA ICE case was built with the same or equivalent properties in terms of geometries, windows, leaks, openings, loads, climate file (IWEC for Stockholm) and opening schedule. Running IDA ICE with default settings (max timestep=1.5 h, tolerance=0.02) led to 16086 timesteps for a four month summer simulation. EnergyPlus was run with (the original) six timesteps per hour, leading to a total of 17712 steps and an execution time of 250 s on a 1.6 MHz Dell Laptop. Adjusting the IDA ICE tolerance to 0.015 gave 17755 steps and an execution time of 127 s, i.e. approximately half the time of EnergyPlus. The three zone case had in IDA ICE 3 442 variables in 118 NMF instances.

Figure 1 shows a duration diagram of timesteps[1] (sorted by size) in the two simulators. The IDA ICE timestep sequence shows a continuous distribution from extremely short steps, well below a minute, up to a few maximum size steps (1.5 h). As is indicated in Figure 2, transients are resolved with very small steps while in "quiet" parts of the simulation long steps are taken. Providing the same time resolution in a fixed timestep tool by using a stepsize equal to the shortest step taken in the variable step tool would lead to huge simulation times.

It is difficult to define a universal criterion for comparing execution times in variable vs. fixed timestep solvers. Comparing the total execution times of a (roughly) equal number of timesteps taken, as we have done here, is clearly not to the advantage of the variable timestep method, which provides a much better time resolution.

[1] Duration diagrams are a standard output form of IDA ICE, normally used for physical variables. Here, the timestep sequence has been plotted in this way. Note that the area under the curve is *not* proportional to the total simulated time.

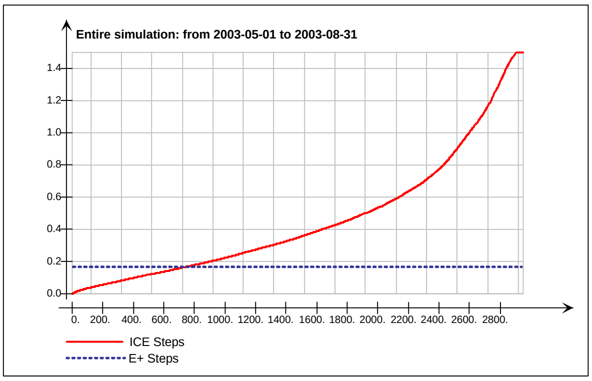

Figure 1. Time steps in ICE and E+

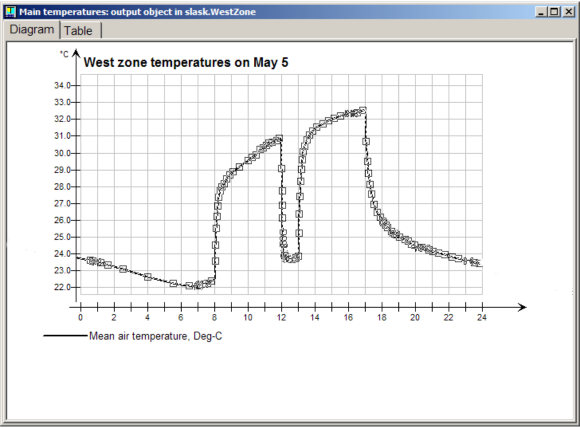

Figure 2. A daily cycle of a variable with marked timesteps

Both IDA ICE and EnergyPlus have IFC import facilities, providing the possibility to create large simulation models with a reasonable effort. In order to get some point of comparison on a larger case, an attempt was made to import the same 53 zone IFC case into both tools. However, the EnergyPlus model showed warnings about not finding floors of the zones and we did not pursue a more detailed comparison due to this problem. Initial runs made with this case without any natural ventilation in the EnergyPlus model (COMIS free) showed that the EnergyPlus model was approximately twice as fast per timestep as the 25 503 variable IDA ICE version.

The results obtained in this small timing study indicates that dismissing DAE methods as being inherently inefficient is indeed a premature conclusion.

PROGRAMMING ENVIRONMENT

DAE development environments such as Dymola, gPROMS [Oh and Pantelides 1996] and, in building simulation, SPARK have been designed to be efficient for proficient mathematical modelers. They have excellent capabilities for formulating and testing large-scale models and building model libraries. However, once a library is ready for production type simulation by less experienced users, limited facilities for model deployment are offered. Today, for these environments, the model developer is usually also the sole user of the model.

A basic ambition with IDA Simulation Environment has been to overcome this problem by providing a setting not only for development but also for model distribution to large groups of end-users, with little appreciation for equation based modeling as such. In IDA ICE, the Advanced level interface offers a model-lab work bench similar to that offered by other DAE environments, providing the user with direct contact with the individual equations, variables and parameters of the mathematical model. However, a great majority of users prefer the tools of the Standard and Wizard level interfaces, where the basic mental concept is that of a building and not of a mathematical model.

A model-lab level user interface requires elements for presentation and interactive manipulation of objects defined by Modelica, NMF or similar. In IDA, this basic set has been extended to form a general programming environment for simulation-oriented graphical applications. This environment gives possibility for definition of arbitrary classes of objects, user presentation of such objects, data mapping between sets of objects (user interface levels), persistent storage and retrieval, scripting, interaction by remote DDE agents, data base facilities etc. All this is defined in interpreted text files, offering each user essentially full control over the internals of an application. Naturally, few users have the desire to customize their application in this way. However, being able to offer critical users full insight into, e.g., data mapping is important for avoiding the natural and healthy engineering aversion for "black-boxes". IDA ICE is a completely transparent "box" with unlimited possibilities for customization. We believe this type of tool is needed to offer useful localized solutions to the large number of building simulation "segments" previously identified.

Today, an increasingly important type of user interface is the rich web client. In IDA, the basic programming framework has been especially designed to facilitate Java script and applet based interfaces running in a web browser, powered by an IDA based simulation engine on the server. A large portion of the native data structures have been mapped to Java script, facilitating advanced web development with minimum effort. The IDA Room wizard is entirely written with this technique and a few IDA Room servers, provides instant, free access to quality dynamic simulation to a large group of European users that otherwise would be unlikely to utilize such technology in their daily design activity.

DESIGN PROCESS INTEGRATION AND IFC

Space does not permit a more thorough discussion of the main issues around product modeling and Industrial Foundation Classes (IFC). A general view of the world that we share in this respect is offered by the DAI initiative [Augenbroe and de Wilde 2003].

Awaiting a more comprehensive solution to the fundamental problems, an IFC 1.5.1 and 2.0 interface for IDA ICE has been developed. Design goals for the implemented interface have been:

1. No particular requirements are posed on the quality and level of population of the IFC model (except that spaces must have been defined); also models that are not a priori intended for simulation are useful. Necessary completion and structural changes are done in the native 3D modeling tool.
2. It is possible to manage repeated design iterations, without having to redo all model completions in the simulator.
3. The user has control of the data mapping between the general model and the native model for simulation.

While the ultimate solutions in this field lie many years into the future, IFC interfaces such as that of IDA ICE in combination with product models servers are presently sufficiently mature for real projects.

INTEGRATION WITH CFD AND OTHER PDE TOOLS

Another area that will offer unlimited topics for future research and development is the connection between lumped parameter tools, such as IDA ICE, and distributed parameter tools, such as CFD environments. This relationship becomes important in several application areas for Modelica tools and we believe that the ease at which such coupling is made will become an important factor for selection of basic DAE solution technology of the future.

A prototype interface between IDA Simulation Environment and the MATLAB multi-physics tool Femlab has been developed. A special IDA component is defined, the equations of which are evaluated in each iteration by a runtime coupling with MATLAB. Jacobians are calculated numerically for this component. (Normally in IDA, symbolically generated analytical Jacobians are used).

Some basic Femlab cases have been tested and for larger problems including Simulink models, runtimes are reduced by several orders of magnitude using this approach.

CONCLUSIONS

In spite of its comparatively tender age and large portion of new technology, IDA ICE has grown to be the building simulator of choice for most HVAC professionals on the markets that so far have been actively pursued and supported (Sweden and Finland). We believe that no other state-of-the-art tool has a similar penetration (about 400 commercial licenses on a market of less than 15 million), showing that given the proper attention also a fairly sophisticated tool can become useful in the profession. Another positive fact is that the Internet based free IDA Room reaches another approximately 1000 regular users in Sweden alone (population of 9 million). IDA Room has recently been introduced on a number of other European markets, but it is yet too early to tell how it will be received

A significant number of NMF modeling efforts have been carried out independently by users. A majority of these projects have been done by undergraduate and graduate students but some also by practitioners, given a two-day course on the Advanced level of ICE and NMF. However, the direct interest in NMF modeling by the profession is somewhat of a disappointment, but is believed to be mostly an indication of cultural and project time frame differences between academia and the consulting profession. An estimate is that 80% of commercial Standard level users never visit the Advanced level, let alone take an interest in NMF modeling.

Practical usage of IFC is another disappointment. In spite of the tremendous savings in thermal modeling time, IFC technology is rarely put to use. A main cause, we believe, is the slow penetration of 3D modeling practice among (at least Swedish) architects. Although, 3D capable CAD tools have been the market standard for several years, a small fraction of mainstream architectural projects result in useful 3D material.

IDA ICE is still in an early stage of its life cycle, and there are many obvious shortcomings that will be corrected. However, the overall conclusion from a technical point of view must be that DAE based modeling as demonstrated by IDA ICE is sufficiently mature for broader commercial application.

The main bottlenecks to a healthy development of building simulation are in our opinion not technical in nature. While revolutionary technologies like 3D CAD, structural FEM and advanced visualization have reached broad penetration in the AEC industry on commercial grounds, building performance simulation is still a basically government funded domain. The key minds in the field are still primarily seeking to please funding bodies, not customers.

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