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DEVELOPMENT OF A NEW TOOL FOR THE CO-SIMULATION USING DECOMPOSITION OF BUILDING AND HVAC SYSTEMS IN SUB SYSTEMS

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ABSTRACT

Towards the achievement of Nearly-Zero Energy Buildings (nZEB), the call for high performance Building Systems (BS) is undeniable. In order to provide, control and reduce the energy used by the BS, complex and sophisticated technologies are more and more introduced. This complex scenario requires computer simulation to evaluate the building performance at design time. To reach this goal, a Building Performance Simulation Tool (BPST) should carefully consider the accuracy of each component's input data and the sensitivity of the simulation results to these uncertainties. In order to face this need and to reduce the time required to gather and input these data into a BPST, some manufactures have already started to develop and distribute over the internet their own libraries of "ready-to-use" components. Such approach is moving in the direction of "autonomous" pieces of computer code, which are able to return the components performance, being any component solved according to its own characteristic internal time scale. This leads to the need of solving a system characterized by multiple time and space scales. The influence of these multiple scales on the accuracy of BPSTs' results is an on-going challenge. To fulfil all those requirements, a tool for the co-simulation of multiple objects (representing walls, air volume and HVAC systems parts) is under implementation and its prototype is here presented. The advantages of this "decomposed description" of the BS, in term of code's maintainability, error control and code readability are also exposed. This prototype aims to be developed by a distributed community, under an open source licence, and to be freely distributed over the internet.

INTRODUCTION

New technologies, with their complexities, have been introduced at all the levels of the Building System. Let's cite integrated HVAC-building element systems, such as Mechanically ventilated Double Skin Façade (Dama et al., 2008), or Thermally Activated Building Systems (TABS) coupled with PCM (Koschenz et al., 2004) or not (Behrendt et al., 2011), or, at the HVAC system level, Ground-Source Heat Pump Systems (Helpin et al., 2011).

To reduce BS's fossil fuel consumption, while increasing indoor comfort, the management of the dynamic behaviour of the BS has also became crucial. On this trail, new control strategies have been developed (Hoogmartens et al, 2011) and a renewed attention on surfaces' temperatures together with operative based thermostat control emerged (Jain et al, 2011 and Kabele et al., 2011).

The only way to investigate the performances of these new possibilities at design-time is through computer simulation. Consequently, new component models are needed and should be introduced in existing BPSTs, bringing with them new dynamics and new sources of uncertainty (Eisenhower et al., 2011).

Here come the first weaknesses of BPSTs, linked with the complexity of their scope, such as:

- they might require numerous (for example geometric ones) input data, being design-time consuming;
- they might require unknown (to the user) or uncertain input data to which the output of the simulation is sensitive (i.e. little inputs' variations would result in relevant outputs' variations), leading to unreliable results;
- they might require complex calculation, being run-time consuming and needing great calculation power.

Some possible answers to these problems, today, are the following:

- interoperability between BPSTs, CADs, BIM softwares and components' Data Bases (DBs) created to gather appropriate and trusted input data (Long et al, 2011), would allow the user to input only a restricted set of information and would reduce errors;
- validation of a model together with its more sensitive and uncertain technical data or "uncertainty aware" models and/or tools (Struck, 2012), would enhance the reliability of BPSTs results, while tools that help the user to understand the behaviour of building's and plant's parts, would reduce users' lack of training/awareness;

- parallel calculation, as cloud computing or as multi-thread solution on multiple CPUs or on graphics processing units (GPUs), would lower the costs of the hardware needed and would reduce the time of complex calculation (Wang et al., 2011 and Zuo et al., 2011).

Summarizing, a BPST should be able to import input data or to use external validated (method and parameter ranges) components, should be easily expanded, incorporating new models and new logics (even developed by a distributed community), should be capable of managing parallel calculations and should have a user-friendly and testing-designed Graphical User Interface (GUI).

Taking advantage of new Information Technologies, that crucially reduce issues linked with the development process and its control, an Object-Oriented (OO) tool for the dynamic simulation of the building system is currently under development. The aim of this project is to investigate the opportunities and drawbacks of an OO decomposition of the physical domain of calculation that parallelize the calculation down to the level of each building system's component (partitions, air node, HVAC components, etc.). This strategy has been chosen, for three main reasons:

- to have the possibility to link to the simulation kernel any building or system component which could incorporate all it needs (from solution algorithms to characteristic data), i.e. a "material" object;
- to have the possibility to parallelize the calculation, without using matrix parallelization routines, in a natural way through the management of the parallel solution of "material" objects;
- to investigate the decomposition of these kind of stiff problems, at the level of each component.

This decomposition will focus on each component nature and characteristics. The ambition of the project, after the validation phase will be ended, is to test different scenarios, chosen to be critical for the numerical schemes used, and to assess the possibility to optimize each component's calculation, selecting the best numerical scheme for its nature and the best space and time discretization for its characteristics.

PROTOTYPE DESCRIPTION

Looking at the examples of new technologies made in the introduction, the starting point in the development of the prototype was the possibility to take into consideration the geometrical aspects of transient heat transfer conduction, radiative exchange and short wave propagation, and to parallelize the calculation even at the building level. This OO "remote procedure" approach has been followed in the development of two old, no more active, projects, i.e. EKS (Clarke JA. 2001) and PSIGene (Zimmermann, 2001).

This strategy has been chosen, together with the parallelization reason, in order to:

- promote the validation of each component, together with its sensitive and uncertain parameters;
- allow the use of proprietary or open components, available under different configurations, such as dll, web services, etc.;
- investigate the usefulness to couple walls solved with different numerical schemes, as a results of their characteristics;
- investigate the possibility to optimize the calculation of each singular object, even by modifying the time step of its own calculation, without interfering with the time step of other objects' calculation, with the aim of reducing round-off error and enhancing accuracy.

The developed prototype is an OO program, written in C# and developed using the .NET Framework and it is now composed of six different projects.

Following the concept of an "enriched modularity" (Mazzarella et al., 2009), the first three projects are respectively:

- a numerical library project,
- a phenomena library project,
- a real components library project,

which may or may not be used by any component (any future independent developer might or might not use them).

Other two projects:

- a modelling project
- and a test project,

have been included in order to manage the distributed development process, taking advantages of the .NET utilities. In particular, the modelling project aims at communicating software architecture's decisions. The layer diagrams, implemented inside this project, might be used to describe and enforce dependencies among components, offering the possibility to validate these dependencies each time a new component is added, with a simple command. The testing project, among other things, automate the control of the results obtained by all the tests developed inside it, to quickly verify that changing some components has not compromised others.

The last element of the prototype is the Main Project, containing the Simulator and the GUIs.

Inside of these projects, we can find different modules, easily identifiable, also thanks to class diagrams, which take care of different physical phenomena, such as:

- the *LWRadiativeModule*, which calculates the gray body mutual radiation factors and communicate to each internal surface its radiative superficial coefficient and mean radiant temperature;
- the *SWRadiativeModule*, that communicate to each surface the solar flux striking on it;
- the *ClimaticDataManager*, that expose the current climatic data, etc. .

For the zone air heat balance three different solution classes has been implemented, of which the first two implement the methods described in the EnergyPlus Engineering Reference manual (October 6, 2012):

- an analytical solution;
- a third order backward difference;
- a theta method finite difference.

All this classes, and any future one, inheriting from a father class, can be exposed automatically to the user in the GUI and can be exchanged one with another without problems, thanks to OO inheritance and to the .NET Framework's Reflection API. The same automatism is used for the convective coefficient calculation modules, and other phenomena modules, such as those related to the sky temperature calculation.

For heat transfer conduction inside building walls, a finite difference method has been implemented, specifically a ϑ*-method* in time and a centred finite difference scheme in space. This ϑ *-method* allows, choosing the ϑ value, to linearly combine the explicit and implicit schemes for the discretization of the time variable (ϑ =1 Implicit; ϑ =0.5 Crank Nicholson (CN); ϑ=0 Explicit).

For long wave radiative exchange, routines to calculate view factors and gray body mutual radiation factors between the partitions (opaque and transparent) have been implemented.

The view factor routine calculates an exact solution, in case of parallel or perpendicular surfaces, and an approximated solution performing a double summation on discrete elements, in other cases. Non-planar surfaces are not yet allowed. The grey factor calculation have been implemented following an implicit and an explicit calculation (Dama et al., 2012).

Multi-zone air network, a shading module and a ground-exchange module have not yet been introduced.

However, the solar radiation entering the zone from the windows is projected on each surface, by the *SWRadiationModule*.

Components related to the HVAC system have not yet been implemented, consequently only free-floating simulations are allowed. The attention is focused on walls surfaces' temperatures, given also their renewed importance concerning comfort and control strategies matters.

PROTOTYPE VALIDATION

Besides some internally developed tests, two different sources have been used for the prototype's validation:

- the ASHRAE 1052-RP Final Report: Development of an Analytical Verification Test Suite for Whole Building Energy Simulation Programs (ASHRAE, 2001)
- the ANSI/ASHRAE Standard 140-2011: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (ANSI/ASHRAE 140-2011)

The validation process has followed two main phases:

- the first phase, whose principal source reference is the ASHRAE 1052-RP Final Report, has been focused on single modules analytical validation;
- the second phase, whose principal source reference is the ANSI/ASHRAE 140-2011 Standard, has been focused on a comparative validation on the whole building system.

Single modules' Analytical validation

From the ASHRAE 1052-RP Final Report, the tests concerning heat transfer by convection and conduction have been used.

The main insights gained from these group of tests, concern the differences in the results obtained for transient conduction via Implicit and CN numerical scheme.

The basic test, since during the simulation each component is subjected to discrete variations (of unknown shape function) in its BCs values, is the ASHRAE 1052-RP Test TC2: Transient Conduction - Step Response.

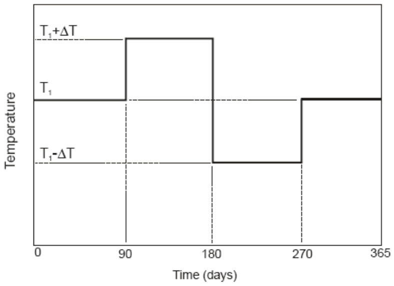

Figure 1: External dry bulb temperature variation

The objective of this test is to find the wall's superficial temperature response to step changes in external dry bulb temperature (Figure 1), when the inside air temperature is held constant.

The wall considered in the test consists of a single homogeneous layer. Constant convection coefficients are taken.

Table 1
Test TC2 Data

Parameter	**Units**	**value**
Thermal conductivity	W/(m*K)	0.14
Density	kg/m^3	500
Specific heat capacity	J/kgK	2500
Thickness	m	0.1
Initial and Inside temp: T$_1$	°C	10
Outside temp step: ΔT	°C	30
Inside Conv Coeff	W/(m^2*K)	3.18
Outside Conv Coeff	W/(m^2*K)	2.607

We have tested a wall component based on a centred finite difference scheme in space and a *ϑ-method* in time numerical scheme, evaluated in the Implicit and CN configurations.

To evaluate the accuracy of both schemes the first tests have been carried out with a space discretization step (Δx) equal to half of the wall thickness and a time discretization step (Δt) of one hour. Even if both methods are unconditionally stable, we have computed the value of significant dimensionless numbers to verify their relevance. This kind of descretization has a *Fourier number* (F_o) equal to 0,161. For the BCs, the stability criterion used is based on the *Biot Number* (*Bi*), as suggested in (Koschenz et al., 2004):

$$F_o \leq 1/[2\cdot(1-\vartheta)\cdot(1+Bi)] \qquad (1)$$

To assess the numerical scheme's accuracy, the wall superficial temperatures obtained are compared with that obtained with an analytical method as reported in Figures 2 and 3 for a rump-up BC and in Figures 4 and 5 for a ramp-down BC. In the following, the differences between the temperature values calculated by numerical schemes and those from the analytical solution are called errors.

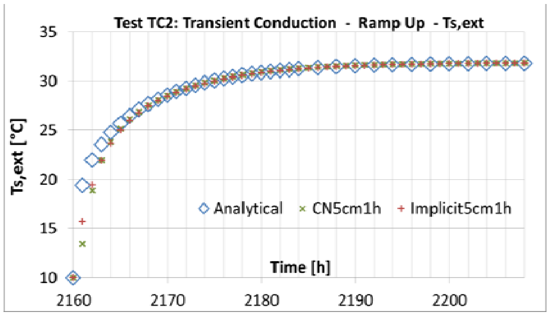

Figure 2: Test TC2 - Ramp Up - Ts,ext

As expected the error on the opposite side of the varying BC is smaller than that on the same side. In the worst case (Ramp Down, $T_{s,ext}$ with CN5cm1h) and in the first hour, this last error is relevant, being of 11.88 °C.

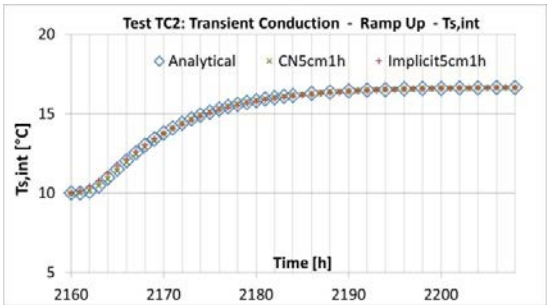

Figure 3: Test TC2 - Ramp Up - Ts,int

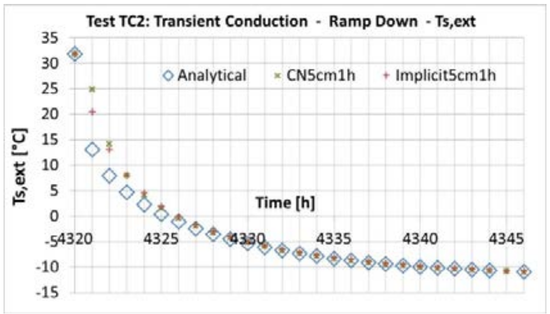

Figure 4: Test TC2 - Ramp Down - Ts,ext

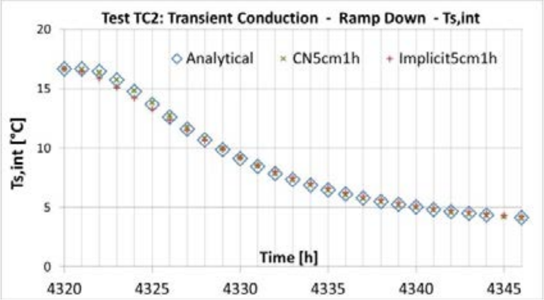

Figure 5: Test TC2 - Ramp Down - Ts,int

Most significant is the better performance of the Implicit scheme versus the CN one due to the shape of the chosen BC. This feature remarks the interdipendece of numerical schemes from the nature of the boundary conditions.

To investigate further the error on the external surface temperature, more specifically that at the first hour after the step (reported in the lasts two columns of Table 3), other combinations of time and space discretization have been tested as summarized in Table 3 (red values do not satisfy the BC stability criterion of Equation 1 and reported in Table 2).

Table 2
BC condition for CN scheme

Δx	Int	Ext
5cm	Fo<0.468	Fo<0.518
2.5cm	Fo<0.638	Fo<0.682
1.25cm	Fo<0.779	Fo<0.811

Table 3
Space and time discretization's combinations

ϑ	**Δx [cm]**	**Δt [h]**	**Fo**	**ErrStep Up [°C]**	**ErrStep Down [°C]**
0.5	5	1	0.161	-5.94	11.88
0.5	5	0.5	0.081	-4.05	8.10
0.5	5	0.25	0.04	-3.30	6.61
0.5	2.5	1	**0.645**	-4.44	8.87
0.5	2.5	0.5	0.323	-1.73	3.47
0.5	2.5	0.25	0.161	-1.09	2.17
0.5	1.25	1	**2.58**	-3.56	7.12
0.5	1.25	0.5	**1.29**	-0.76	1.52
0.5	1.25	0.25	**0.645**	-0.54	1.09
1	5	1	0.161	-3.71	7.42
1	5	0.5	0.081	-3.25	6.50
1	5	0.25	0.04	-2.97	5.94
1	2.5	1	**0.645**	-2.18	4.35
1	2.5	0.5	0.323	-1.46	2.92
1	2.5	0.25	0.161	-1.02	2.04
1	1.25	1	2.58	-1.51	3.02
1	1.25	0.5	1.29	-0.82	1.65
1	1.25	0.25	**0.645**	-0.45	0.90

As expected, the CN scheme reduces its errors, while reducing the time step, more rapidly than the Implicit one, even if, for this specific BC (step), the Implicit scheme is more accurate than the other.

Since the change in external BC is very rapid, the time step play a crucial role. To have a F_o close to 0.5 (Hensen et al, 1994) with a time step of 15 min we have to reduce the space distretization from 5 cm to 1.25 cm, which leads, for a sudden step of 60 °C, with an Implicit scheme, to an error of 0.9 °C while the "three nodes per layer" rule, leads to a corrisponding error of 5.94 °C.

Even if these tests are relative to a quite capacitive wall and to a BC step change not so representative of any common situation, these results have shown the usefulness of having developed a GUI dedicated to test walls behaviour. Here, the developer and/or the advanced user can test results obtained, by changing:

- the numerical scheme;
- the space and time discretization;
- one or more (compatible) boundary condition (an imposed superficial temperature, a flux or a mixed condition);
- the shape function for each boundary condition.

Nonetheless, one of the objectives of the current project is the identification and implementation of rules (like those identified in Hensen et al., 1994 or in Tuomaala et al., 2000) that, taking into consideration the F_o and, for example, the current BC variations, choose the more convenient time and space discretization for each singular element (e.g. a wall).

To briefly cite the other relevant modules validation:

- the view factor routines have been validated on the Case 600 of the ANSI/ASHRAE 140-2011 Standard, comparing the prototype results with spreadsheet calculated factors and with those produced by another BPST, i.e. Esp-r;
- the grey body mutual radiation factor routines (implicit and explicit) have been tested with the help of a Matlab file, given the view factor matrix and the emissivity of the surfaces;
- the projection of sun radiation from the windows to the indoor surfaces has been also tested with spreadsheet calculation.

Whole system's Comparative validation

From the ANSI/ASHRAE 140-2011 Standard all the free floating case studies have been tested, i.e.:

- Case 600FF (low mass);
- Case 650FF (low mass & night ventilation);
- Case 900FF (high mass);
- Case 950FF (high mass & night ventilation).

The data available with their hourly profile, for each case and reported software, are the external solar radiation received by two wall's expositions and the zone air temperature during one day. This last datum is available respectively for:

- Case 600FF and Case 900FF for the 4th of January;
- Case 650FF and Case 950FF for the 27th of July.

It would have been useful to have also the temperature of the outside and inside surfaces of each wall, ceiling, etc., since especially these last information are relevant for comfort's considerations and control strategies (Jain et al, 2011 and Kabele et al., 2011).

In order to better analyse the consistency of our model with the results obtained by other software, the possibility to have the input files of each of the ANSI/ASHRAE 140-2011 Standard test case for different softwares, updated at their latest release, has been used.

As reference values, the hourly zone air temperatures have been averaged among all the available results (i.e. those of the BPSTs reported into the Standard 140). This set of average values has been used to assess the prototype performance.

Since the validation process has led to similar results for the four cases, in the following only the results obtained for the Case600FF, will be presented.

The first results from the prototype have been obtained with a very rough discretization of the wall layer, with just three nodes for each of them, leading to high *Fourier Numbers*. With this rough approach, the results are not far from the average values.

If we look at the results for the Case 600FF we can see, in Figure 6, that results close to the average hourly values have been obtained by the prototype, with an implicit method for the heat transfer conduction, a time step of one hour and an implicit method for the zone air heat balance.

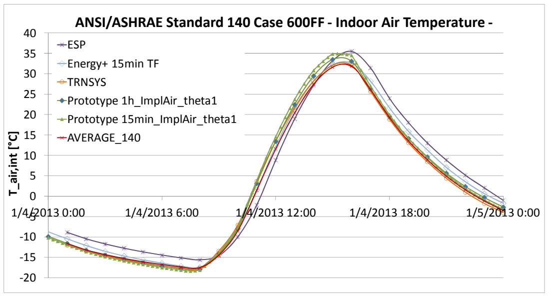

Figure 6: Case 600FF - validated software's results

In the first and second column of Table 4, we have reported the maximum, and minimum difference between the hourly value of indoor air temperature obtained by each software and the average value obtained by the software that have participated to the validation. In the third column, we have shown the Euclidean norm (l^2-norm) of these hourly differences calculated during the whole day. We have calculated these values, even if, being missed the "correct" solution, there is the possibility that the more accurate software gives a solution distant from the average value, as stated also in the standard.

Table 4
Case 600FF results comparisons

BPST	**MAX °C**	**MIN °C**	**l^2-norm °C**
ESP	5.33	-3.61	14.95
BLAST	1.19	-1.85	4.31
DOE2.1D	2.17	-1.22	5.77
SRES/SUN	-0.17	-0.60	2.13
S3PAS	-0.11	-2.23	5.04
TRNSYS	2.24	-0.61	4.18
TASE	-0.89	-3.63	9.87
Energy+ 15 min	2.42	0.03	6.59
Energy+ 1h	3.76	-5.89	14.16
Energy+ CN 3 min	3.71	-0.56	8.10
Energy+ Impl 3 min	3.53	-0.55	7.79
Prototype 1h	1.75	-0.40	4.80
Prototype 15min	3.07	-0.71	7.16

We can see, from Table 4 and Figure 6, that we have higher values of mid-day air temperatures if we reduce the time step to 15 min as that used by Energy+ if Conduction Transfer Functions (CTF) are chosen for walls calculation.

However, also Energy+ obtains higher mid-day temperatures changing the solution of heat transfer to conduction calculation, from CTF to an implicit finite difference scheme (for which a time step of 3 min is imposed), as can be seen also in Figure 7.

The prototype gives slightly higher value of mid-day air temperatures if we reduce the time step to 3 minutes as imposed by Energy+ if finite difference schemes are used for heat conduction.

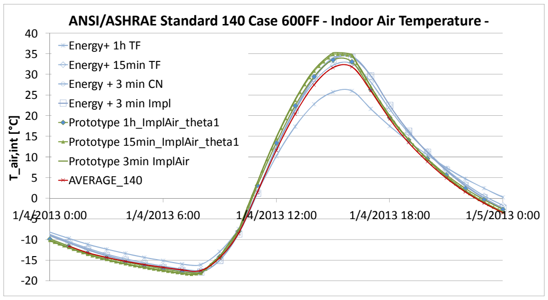

Figure 7: Case 600FF - CTF vs. FD numerical resolution

To have an idea of the differences in results sensitivity to time step variations when using a FD scheme for heat conduction, against using CTF, we have tried different time steps with CTF, in Energy+. Choosing a 1 h time step, the tool has given a warning, suggesting the use of at least a 15 min time step. For the 3 minutes time-step, no warning has been printed out (even if in the Energy+ Engineering Reference manual, this approach is not suggested, especially for heavy constructions, which is not the current case) and we have obtained again higher temperature values, but also a shift in the time response, as can be seen in Figure 8.

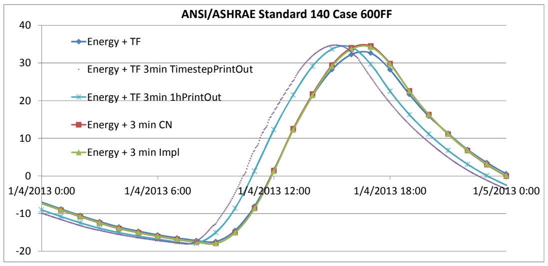

Figure 8: Case 600FF - CTF vs. FD time step sensitivity

As shown, using Energy+, as a "blind" user, it gives some results not immediately comprehensible. If there is some reason for which CTF should not be used with a 3 min time step with this type of constructions, the CTF module should have handled it automatically avoiding its use or at least pointing out a warning, as in the other cases (the 1 h time step and the 3 min time step for the FD scheme).
Following these considerations, it might be useful, to structure each module with different usage levels from the design stage. These levels of fruition might be:

- a "blind" level, where only the use of embedded parameters values is allowed, or

for which sensitive data are calculated internally by the module, in a "safe" mode;
- an "expert" level, for which the user can modify some sensitive parameters, for particular case studies or research inquiries;
- a developer level, where the class definition of the module is editable by the developer.

To summarize, the BPST fruition level should be intrinsically defined in each module and not only demanded to an "intelligent graphical user interface".

PROTOTYPE DEVELOPMENT PROCEDURE

Another aspect of the on-going project is the development and maintenance of a protocol to allow each team member to have and give the right information at the right time, since understanding the various aspects of the project, including schedule, scope, risks, resource issues, and so on, is critical.

Being the project's objective, the development of an Open Source code, own by a distributed community, a structured web based information repository is mandatory to assure models diffusion and maintenance. This repository will have the standard structure that helps in the identification of the different aspects of the software-development life-cycle, such as:

- project management (development) that can benefit of:
  - modelling projects to communicate architectural aspects,
  - class and sequence diagrams to help in understanding/browsing existing code,
  - team management rules, that grant different permissions/accesses to the project to different team members on the basis of their responsibilities/roles;
- version control;
- test case management and validation (through cross validation in order to have more than one person that legitimates the tests done);
- build automation (distribution);
- reporting.

Besides this, a full references and technical reports DB will be handled supporting each implemented algorithm from the theoretical, physical and numerical point of view. This to allow any user to be known about the theoretical and numerical background of any implemented component and of its validation tests.

ON GOING WORK

Currently are under development the modules related to:

- shading calculation;
- multi-zone solution (inter-zone air flow);
- ground to building heat transfer;
- HVAC system controls and actuators.

The next validation tests will comprehend:

- the remaining test cases of the ANSI/ASHRAE 140-2011 Standard;
- the empirical validation tests described in the IEA Empirical Validation of Thermal Building Simulation Programs Using Test Room Data (IEA, 1994).

Is also under development the identification of discretization strategies that, during the simulation, adapt the time and eventually the space discretization of an object, as a reaction to the variation velocity of the identified "leading" dynamic driving forces of outdoor and indoor environments, in order to reduce discretization errors.

Up to now (i.e. for the tested cases), the convergence of the zone air node temperature is quite good, even if the case of different time steps for different objects has not yet been tested. The "material" object oriented approach is also under testing by employing in the same room wall components solved with different numerical schemes.

CONCLUSION

A new Object Oriented Building Performance Simulation Tool is under development. We have here described the main aims and aspects of this prototype, the first validation tests and the on-going developments.

This prototype decomposes the building system's domain down to the level of each building element (wall, air-node, etc.), to solve the BPS problem in a "natural" parallel way (i.e. without using matrix parallelization techniques). The OO structure also allows having different space and time scales in each module in a simple way. The final effort of the project is to identify convergence rules that lead to stable solutions when different "independent" BS objects are involved in the simulation.

This decomposition regards not only the calculation, but also the documentation, validation and optimization of each module. Once each module has been validated, global validation methods can be more confidently applied.

For critical components, "customized" modules (embedding critical data or solution options to simulate that specific component) could be defined along with a generic module. This approach would allow different fruition levels (blind or expert), preventing the use of a component outside its validity range.

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