

INTERNET-BASED MULTI-DOMAIN BUILDING PERFORMANCE SIMULATION AND SEAMLESS INTEGRATION WITH CAD FOR EARLY DESIGN SUPPORT

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ABSTRACT

SEMPER, which was originally developed at Carnegie Mellon University (CMU), is an active, multi-domain, space-based, object-oriented design support tool for integrated building performance computing. This paper discusses the key findings of a collaborative research project between National University of Singapore, Carnegie Mellon University and Temasek Polytechnic to modify and transform SEMPER prototype 1 into SEMPER-II (S2), as an internet-based computational design support environment in order to facilitate geographically distributed design collaboration. The working details of the multi-domain Thermal Suite within S2 and the integration of the S2 GUI with a CAD tool are specifically discussed with illustrative case studies.

BACKGROUND

With the increasing complexity of building design and performance evaluation calling for trans-disciplinary participation, computational tools must be re-conceptualized and re-engineered to facilitate this and the possibility of geographically distributed expertise. Such a system must not only be capable of supporting concurrent performance evaluation of building design and engineering across domains, but be accessible across geographically distributed environments through both synchronous and asynchronous modes of communication.

This paper discusses the key findings of a research project to develop an internet-based computational design support environment SEMPER-II, based upon the original SEMPER, an active, multi-aspect prototype design and simulation environment that incorporates an object-oriented, space-based design tool, with dynamic links to different building performance evaluation tools [Mahdavi et.al. 1995]. S2 realized SEMPER on the Internet, toward supporting geographically distributed users in collaborative performance-based building design. The S2 development was pursued within the framework of an international collaboration between three institutions, NUS (National University of Singapore), CMU (Carnegie Mellon University), and TP (Temasek

Polytechnic, Singapore) [A. Mahdavi et. al. 2000, 2001, 2002].

THE SEMPER-II (S2) ENVIRONMENT

The S2 system has been presented in our previous papers (Mahdavi et. al. 1999, Lam, et. al. 2001). The following sections give a brief overview of the S2 simulation environment.

Building Representation with SOM & DOM

The building representation in S2 is defined as the "Shared Object Model" (or "SOM"). This is an application-specific hierarchically structured template (a class hierarchy in object-oriented programming terms) to capture the essential elements of a building and their properties, to the extent required by the simulation applications in the S2 environment. SOM does not contain the entire building information. It contains a tightly structured "notation" of constitutive building elements, with pointers to (addresses for) the detailed information on such elements in the data repository for the persistent storage of such information.

While SOM may allow retrieving the necessary building geometry, material, and context information that the S2 applications require, it is not sufficient on its own for a building performance simulation application to function. For each disciplinary domain, the "Domain Object Model" (DOM) must be generated upon filtration and modification of information in SOM according to the specific view of the building in that domain. In addition, domain specific entities (e.g., finite control volumes in numeric heat and mass transfer computation) may have to be added to what is inherited from the SOM. While developing technologies for automated SOM-to-DOM mapping is non-trivial, the S2 project, which focuses on integrated building energy, HVAC and airflow analysis, has shown that, for certain applications and inquiries within a certain range of informational resolution, such mapping is both possible and effective. [Lam K. P., et. al. 2001, 2002].

Within the framework of the SEMPER project, a functional "homology-based" SOM-to-DOM mapping technology for a number of applications has been developed. This technology uses the configurational isomorphism between SOM and various DOMs to derive the latter – automatically – from the former [Mahdavi, et.al. 1995, 1997]. Though such a mapping technology may not necessarily work for all domains and is independent of the informational resolution of the pertinent inquiries, the S2 project successfully demonstrates the feasibility of this mapping technology.

Distributed Multi-agent Collaboration Protocol

S2 Kernel:

The S2-Kernel is the functional core of the system and is implemented in Java. It populates the Shared Object Model (SOM) and maintains its consistency. The input to the S2-Kernel is provided by the Graphical User Interface (GUI). S2-Kernel processes this input in view of SOM's informational requirements.

The S2-Kernel residing in the server, uses a multi-user object database to store the SOM. This makes the SOM available to the rest of the S2 system (e.g., applications). When simulations are to be conducted, the applications communicate with the S2-Kernel. On a user's computer, the S2-Kernel uses a lightweight single-user database for SOM persistence. On connection to the Hub, the SOM is ready for upload to the server. The transfer happens with a single call (objects are sent by-value), incurring any network delay penalty associated with the call, only once.

The semantic information is kept in "type" objects (e.g., construction and material properties, etc.). These type objects are kept in separate databases that can be customized and/or maintained by manufacturers. Only a tag to the "type" is appended to a list of tags for each object and there is no restriction on the number of tags that a building element can hold. This provides a simple plug-in mechanism for future applications.

Graphical User Interface:

The S2 graphical user interface (GUI) allows users to create and edit building descriptions. Current CAD models typically lack sufficient information to provide the necessary input for the S2-Kernel. For example, most CAD systems do not have a "space" (room) entity and frequently represent the building only as a configuration of walls and slabs. However, most simulation applications depend on an understanding of "space" as a "void" with surfaces of enclosure components as its boundary. Moreover, the space element is used as a container for many semantic attributes that are used during simulation (e.g., type of activity, occupancy schedule, etc.). The S2 GUI was

designed to be simple and lightweight for simple editing and/or viewing on computers where CAD systems may not be available.

In an effort to demonstrate the usability of S2 to the world of design professionals, ArchiCAD, an object oriented CAD tool, was used as a case in point. An interface has been developed linking ArchiCAD and S2 whereby the building geometry can be directly transferred from the CAD model to S2 for simulation. More details of this interface development will be given later in this paper.

Hub and the Data Repository:

The Hub is the communication coordination center. It is the entry point to the rest of the system for users. Its address is made known to everyone. It authenticates users, keeps track of available resources, and connects users to resources on-demand.

The S2-Kernel uses a modular interface for data access. Although any database can be used with the system, currently S2 uses an object-oriented database for its central, multi-user repository. This repository not only holds project (design) information, but also organizes "type" objects that provide various semantic qualifications to building elements.

Global Communication Infrastructure

S2 has a modular architecture that allows for future extensions. It uses the Object Management Group's (OMG) Common Object Request Broker Architecture (CORBA) technology, which is language and platform-independent, for communication between its various components (Otte, et. al. 1996). Most of S2 application engines are developed using C++. However the core components and the user interface is developed using Java. CORBA development has enabled these components to come together with relative ease and without any user-written language-mapping code and without restricting users to a specific platform. Thus, it is possible to envision applications – new or existing – from any domain and with any development environment to make use of S2 capabilities.

The system database and library are located in both NUS and TP. This includes the project database running on one server and the Hub on another server, which is the entry point for any Graphic User Interface (GUI) and user authentication. S2-Kernels are spawned on-demand by the Hub for each project that a user remotely opens through the S2 GUI. The Thermal Suite applications, which are described in the next section, are also deployed in both TP and NUS. The above illustrates the flexibility in the system in that any number of servers running databases or applications can be deployed anywhere in the world.

When an application or a database server starts up, it registers with the Hub and makes its location on the network known. Users access S2 by establishing a connection and authenticating with the Hub. To run simulations, users specify the engines through the GUI. The Hub coordinates the simulation processes by sending the project information to the appropriate servers. It also notifies the user as results become available.

THE THERMAL SUITE

The Thermal Suite is a "super-application", involving three originally stand-alone S2 simulation modules, namely NODEM, HVAC and BACH, for building energy analysis, HVAC system simulation, and air flow analysis, respectively. These modules are realized as distributed simulation objects, accessible through the web. CORBA is used as the communication framework between the modules. A central coordinating application (Thermal_App) is implemented to act as a controller and mediator between the modules. The three modules of the Thermal Suite can run independently or in tandem (see Table 1), depending on the nature of the user's performance query.

Table 1. Activated Thermal Suite modules as a function of the performance assessment scenario

Simulation scenarios	NODEM	HVAC	BACH
Comprehensive thermal analysis	✓	✓	✓
Climatized building with sealed envelope	✓	✓	
Passive building with natural ventilation	✓		✓
Load calculation	✓		

The Modules

NODEM (Mahdavi, et. al. 1995, Mathew 1996), the energy analysis module, uses the same heat-balance technique as other detailed heat-balance simulation programs (Clarke 1985), but is designed in a manner that allows for operation with a "coarse" representation of the building. According to the local weather data and operation schedules, NODEM computes heating, cooling, and electrical loads as well as space temperature profiles.

The HVAC module (Brahme 1999) has a consistent modeling approach throughout the building design process, which is applicable in the early design process and yet comprehensive enough as an evaluation tool. Its use of a component-based modeling approach makes it scalable and allows designers to model new systems in addition to modeling pre-defined system types. The HVAC module computes the properties of the supply and return air for a given operation schedule. It calculates the system energy consumption

and is also capable of generating a default terminal layout and distribution network of typical HVAC systems.

BACH (Wong and Mahdavi 2000, Mahdavi 2000, Wong, et. al. 2003), the airflow model follows a hybrid multi-zone and CFD approach. It allows three-dimensional analysis of airflow and contaminant dispersal. Given building geometry information (spaces, enclosures, and openings), BACH uses wind and temperature difference information to compute the air change rate for each space. Automated conversion of general building design representation into an appropriate domain representation for air flow analysis is provided for both orthogonal and non-orthogonal building geometries.

Data Exchange Between the Modules

Figure 1 illustrates schematically the data exchange between the three modules of the thermal suite (for an air-based HVAC system). NODEM sends the temperature data of each cell to both HVAC and BACH. In return, HVAC provides NODEM with information on heating/cooling temperature and volume, while BACH provides NODEM with air flow volumes due to ventilation and infiltration. HVAC also provides BACH with supply air conditions (relative humidity, CO₂ concentration) for the purposes of air quality analysis.

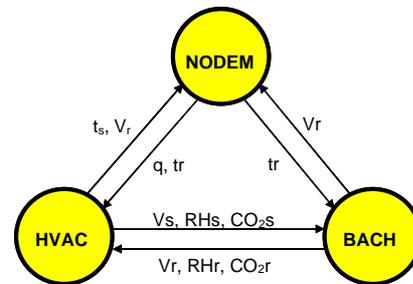


Figure 1. The data exchange between the thermal suite modules. (*q*: Space load, *tr*: Space temperature, *ts*: Supply air temperature, *Vr*: Air flow volume, natural ventilation *Vs*: Supply air flow volume, *RHr*: Space relative humidity, *RHs*: Supply air relative humidity, *CO₂ r*: Space carbon dioxide level, *CO₂ s*: Supply air carbon dioxide level).

Distributed Communication

In order to implement the coupling between the three simulation modules, certain communication protocol has to be established for the necessary data exchange between the modules. If the different modules run concurrently on the same machine, this can be done

via data files for the interactive data to be written to or read from. But this method does not work if the simulation modules run in a distributed mode on separate machines over a network or Internet. In the latter case, technologies for distributed computing, such as CORBA and RMI, need to be applied. In the Thermal Suite, CORBA is used as the communication framework. The simulation modules are wrapped as a distributed object by CORBA defined interfaces. This allows the Thermal Suite modules coded in C/C++ to be called from client programs written in other languages, for example, a Java coded GUI. CORBA based development also supports a modular structure that simplifies the addition of future components to a system.

The CORBA-based modules are called NodemApp, HvacApp and BachApp. Since different simulation modules may or may not run in tandem, a ThermalApp interface was developed to regulate the sequence of execution. Also, it a) allows CORBA-based connections to other S2 components, b) is responsible for the time step coordination, and c) facilitates data exchange between the thermal suite modules at each time step over the network. The ThermalApp obtains the specifics of the client's thermal assessment query and instantiates the pertinent module(s) of the thermal suite accordingly. A schematic diagram for the main interface operations and the connections to and among the modules is given in Figure 2.

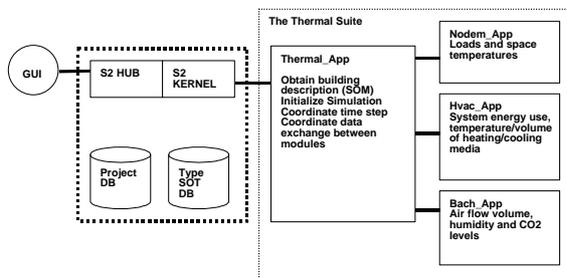


Figure 2. Schematic illustration of the Thermal Suite Architecture

The call from the S2 client will pass the reference of the S2 SOM along with the call to ThermalApp, and the ThermalApp will further forward the reference to the simulation modules it invokes. It should be noted that mapping is necessary for the data exchange among the modules as their coordinate and nodal systems may differ from each other. Mapping is also necessary for the required information from SOM to DOM. Generally, the simulation modules use homology-based mapping, and two types of mapping operations, namely object-object mapping and object-attribute mapping, are used (Mahdavi, et. al. 1999).

INTEGRATION WITH CAD

In an effort to demonstrate the usability of S2 to the world of design professionals, ArchiCAD, a popular object oriented CAD tool, was used as a case in point. ArchiCAD is one of the few CAD software which allows a space-based representation of a building, a necessity for building performance simulation. An interface has been developed linking ArchiCAD and S2 whereby the building geometry can be directly transferred from the CAD model to S2 for simulation.

Two ArchiCAD API add-ons were developed for S2 integration to ArchiCAD: "s2 format" and "launch S2 GUI". The "s2 format" add-on is to dump from ArchiCAD as much building information as necessary for S2 simulation. This add-on is available as one of the "Save As" options, i.e., once a building design is done with ArchiCAD, the add-on enables the designer to save the project as "s2 format" in an .SP2 file, which is readable by S2 GUI. The prototype add-on output mainly building geometry information including spaces, windows, doors, and HVAC terminals. The "launch S2 GUI" add-on is one of the S2 menu items for launch the S2 interface from within the ArchiCAD. Figure 3 shows the launch of S2 under the ArchiCAD environment.

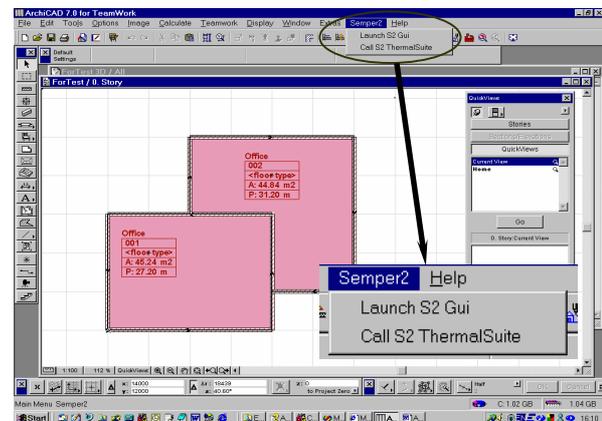


Figure 3. The "Semper-II" menu and its two S2 tools within the ArchiCAD environment.

S2 uses the type of "wire-frame" spaces for simulation purpose. ArchiCAD does not provide directly this type building space information. The needed information is extracted from ArchiCAD zone/room. Use of this approach implies that a user will need to zone the spaces first before the add-on could output the relevant space information for S2 simulation.

It was noticed that ArchiCAD has three geometry methods for creating zones of three types, i.e., the manually created zones, the zones surrounded by inner edges of the walls, and the zones surrounded by the reference lines of the walls, respectively. Not all the three types of zone can be directly mapped to S2 space

satisfactorily because they may not generate consistent building geometry in wire-frame. For example, for the zones surrounded by the inner edges of the walls, it will possibly generate two different wall lines in the wire-frame for even the same wall. This is not acceptable by the S2 model. Different approaches have been implemented in the add-on to transform consistently the different types of zones to the ArchiCAD wall reference line based spaces.

In addition to the building spaces, the API add-on can also output information of windows, doors and HVAC terminals for S2 simulation.

SAMPLE SIMULATION AND RESULTS

The CORBA-based connections and the prototype thermal suite integration have been successfully demonstrated.

The following figures show the screen captures of the S2 GUI, from which a user can design a building, set configurations, and call for Thermal Suite simulations.

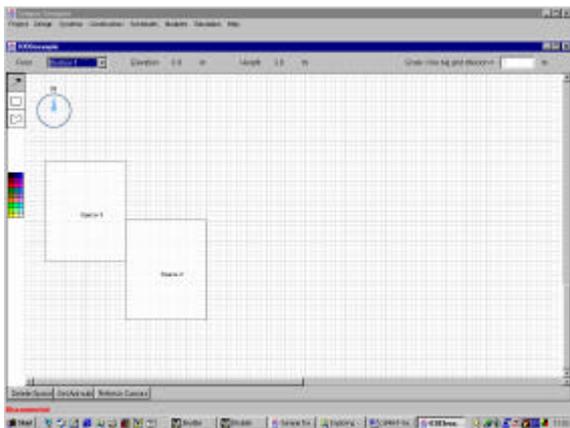


Figure 4. The S2 GUI

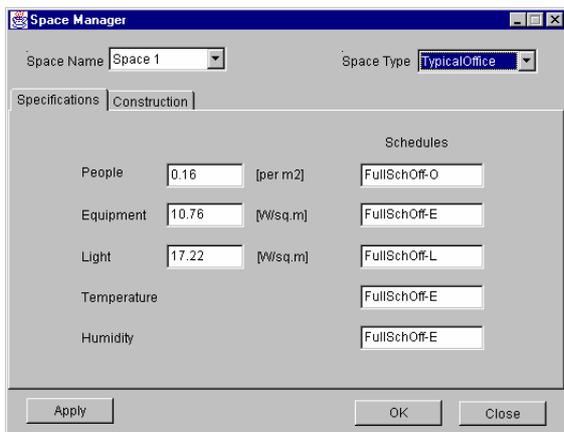


Figure 5. S2 GUI's interface for space specifications

The GUI can also import the building design done by ArchiCAD through the .SP2 file generated by the "s2 format" add-on. The user can set the internal loads and relevant schedule for each of the spaces (Figure 5) as well as the construction types (Figure 6).

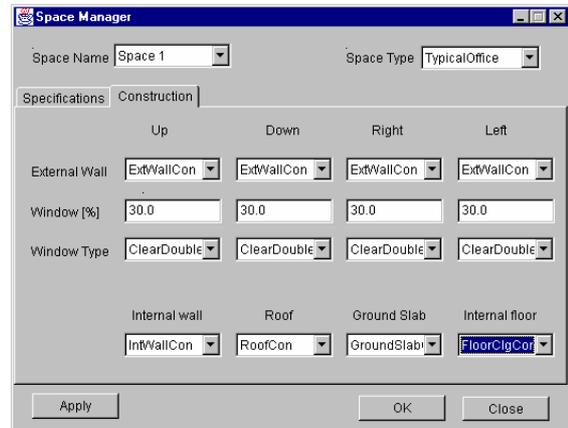


Figure 6. S2 GUI's interface for construction types

The GUI also provides the interface for setting simulation parameters which are written into a local datastore file and then sent to the remote simulation engine for analysis. The simulation settings are set by the user, during which selection of simulation modules can be made either of the individual modules or in combinations of the modules based on the user's performance query. Figure 7 demonstrates the interface for simulation settings.

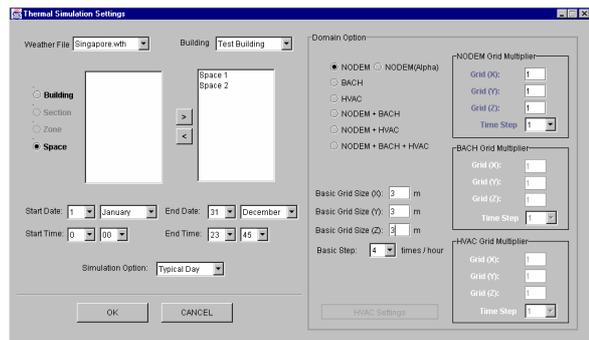


Figure 7. The interface for simulation settings

An advanced option of thermal simulation settings is also available for users to change the settings for specific HVAC system types. These parameters are the clients handle to the parametric simulation of systems that may have been added from external input such as that from other CAD software.

Figure 8 gives the passive design thermal simulation results for a two-space building in Pittsburgh (January). For the passive simulation, only the NODEM simulation module was selected. The grid size is 3m and the number of time steps per hour is 6 (in 10 min

time steps). The prescribed construction types were selected from the available lists.

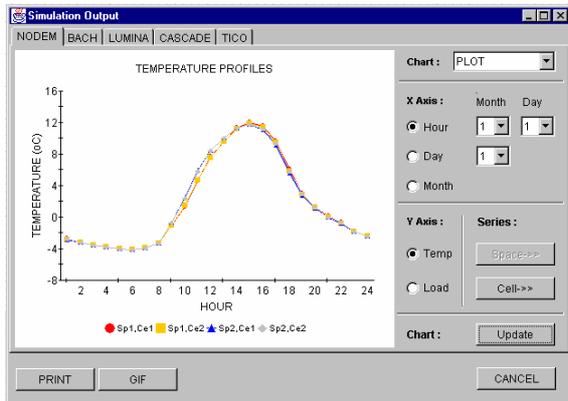


Figure 8. Passive design simulation results

Figure 9 shows the active design thermal analysis with load calculation for the sample two space building with Singapore weather. This was done by alpha version of NODEM which has certain HVAC capabilities.

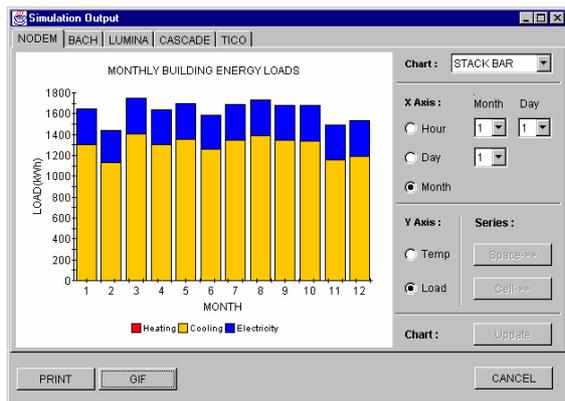


Figure 9. Active design simulation results with thermal load calculation

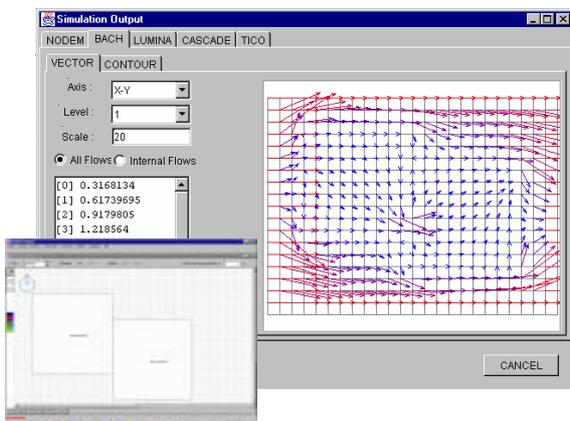


Figure 10. Integrated thermal and airflow simulation (only airflow results shown)

Figure 10 demonstrates the integrated simulation with both thermal and airflow analyses. Both NODEM and

BACH were involved. The grid size for NODEM is 3m while the for BACH is 1m to allow sufficient resolution for the airflow simulation. As BACH is very time consuming, for the sample simulation the time step for BACH is one hour while the time step for NODEM is 10 minutes. The successful demonstration for the coupled simulation between different modules with respective grid sizes and time steps shows that the implemented algorithms for mapping of coordinate and time step, as well as for the data, are feasible and effective.

DISCUSSION

There are various efforts in developing collaborative tools, such as the EU COMBINE project which aimed at "establishing a data infrastructure and tools for managing the information exchange in a building design team". This was done using an Integrated Data Model (IDM). In the case of S2, a similar approach using a common data model (the DOM) is used and further work is being done to integrate this with data communication standards such as the Industry Foundation Class (IFC) structure. A major thrust in the S2 development has also been its implementation as a web-based collaborative design tool.

The foundations of the object modeling, the technologies used and their implementation have been reported in our earlier papers, which represent a conceptual roadmap for the reported implementation (Mahdavi 1996, Lam, et. al. 2001, 2002a). Work is currently in progress to capitalize on the shared object model and databases envisaged within the IFC structure. The S2 research team has in fact embarked on, and completed an exploratory research project titled "Mapping of Industry Building Product Model for Detailed Thermal Simulation and Analysis" (Lam, et. al. 2002b). The preliminary results positively indicate that a link can effectively be established between S2 and the IFC compliant systems (e.g., CAD software) to facilitate sharing of model data for performance simulation. This testifies to the true robustness of the original S2 concept and architecture in offering flexibility and adaptability of the simulation environment to continuous evolution of IT in the building industry.

CONCLUSION

This paper highlighted some of the key technical deliverables of this collaborative research effort. They include:

1. The implementation of the internet-based communication infrastructure for the various components (e.g., hub and kernel) and applications of S2 using the Common Object Request Broker Architecture (CORBA) technology;

2. The development of a link between S2 and a commercial object-based architectural CAD software application (ArchiCAD) to enable the direct transfer of spatial information of the architectural design layout from the CAD model into the S2 environment. This is an essential functionality required to address and overcome a critical barrier in professional practice that has hindered the pervasive use of performance simulation tools in the building industry;

3. The Implementation of the "Thermal Suite" application, which dynamically links the existing "stand-alone" simulation applications, viz., NODEM (for thermal and energy simulation), BACH (for air flow simulation) and HVAC (for heating, ventilating and air-conditioning system simulation), to provide an integrated and more "realistic" approach to thermal performance analysis of building design;

4. The enhancement of the capability of the S2 Hub to handle multiple logins and queuing of multiple requests for simulation runs, as well as providing a file management system with versioning function, for the end-user.

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