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1 **INTEGRATED BUILDING DESIGN, INFORMATION AND SIMULATION**
2 **MODELLING: THE NEED FOR A NEW HIERARCHY**

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ABSTRACT

The need to reduce radically the energy used by buildings is leading to new design practices. Current design and simulation software are used in very different ways, with energy simulation generally employed to check energy code compliance after the design stages are mostly finished. This linear approach to working practices, the modelling methods used and poor interoperability inhibit iterative design practices. This paper outlines a case study to elicit early software requirements for combined simulation and design software. The barriers to this type of integrated software are discussed. Finally, a change to the hierarchy of existing interoperable languages is proposed.

INTRODUCTION

The key conclusion of the *Working Group III: Mitigation of Climate Change* is that substantial reductions in carbon dioxide emissions from energy use in buildings can be achieved over the coming years. Mature technological, systemic and building management options already exist for greater energy efficiency. It is estimated that there could be over 75% of energy savings for new buildings, through designing and operating buildings as complete systems. They state that realising low carbon buildings will require significant changes in practice and policy to enhance what is currently happening. “An integrated design approach is required to ensure that the architectural elements and the engineering systems work effectively together.” (Intergovernmental Panel on Climate Change, 2007)

The use of BPS [Building performance Simulation] software, as part of an iterative process throughout the design stages, is an important aid to an integrated approach to the design of buildings. There are many aspects to designing buildings that, apart from low energy, make them a joy in which to work and live. However, there is a danger that if low energy becomes the dominant design factor, architectural creativity may be compromised. The ability to make easy use of BPS would enable the architect to explore a range of design options whilst checking their energy performance. The use of BPS at the present time is limited (Hensen & Lamberts, 2011). In general it is restricted to iconic projects

where the budget is sufficiently large to enable the employment of specialist consultants. This paper is concerned with how BPS could be more accessible to small practices with limited budgets.

This paper is organized as follows: the next section discuss the need for new design practices to involve the use of BPS; the results from a case study to determine software requirements for the development of an integrated toolset are then reported; the barriers to integrated software are discussed and finally the possibility of changes to the hierarchy of currently used interoperable languages is discussed.

NEW DESIGN PRACTICES

The architectural and construction professions are becoming subject to ever-increasing legislation, stringent building codes and guidelines relating to energy use and sustainability. There is concern from both academia and government regarding the sheer scale of changes in praxis facing the construction industry in the next 20-30 years (Oreszczyn & Lowe, 2010) (Department for Business, Innovation and Skills, 2010).

Traditionally, rules of thumb and simplified calculations have been used to guide thermal performance considerations during the early design stages of buildings. It is only after the design has been finalised that external energy analysts have been involved to analyse the final design solution. Many of the decisions that affect energy demand are taken during the early design phases when simulation is not currently used (Hensen & Lamberts, 2011). Architectural design is an iterative process with architects cycling through alternative solutions, testing, analyzing and refining their solution as it is developed. Figure 1 illustrates this process against time. As shown, involving thermal simulation in the iterative design process causes it to be interrupted, and effectively halted at intervals, by the need for the design to be analyzed by heating and ventilation engineers, as shown by the breaks in the cycle. Often this is only a check for code compliance. The number of simulations carried out by consultants will be affected by both the cost of employing external consultants and the delay in the architectural design process whilst the proposed building is analyzed.

New low energy requirements will necessitate regular quantitative analysis to predict the energy demands of the proposal as the design is developed.

Large or prestigious projects, designed by large design firms will either have their own in-house energy analysts or be able to afford external consultants. However, there is concern, in the UK at least, as to how smaller practices will cope with limited access to tools and expertise (Technology Strategy Board, 2009). There is a growing consensus within the literature of the need for integrated design and building performance simulation software (J. Clarke, 2001) (Papamichael & Pal, 2002) (Augenbroe, 2002) (J. L. M. Hensen, 2004) (Eastman, Teicholz, Sacks, & Liston, 2011). This is seen as a necessity to enable the replacement of traditional sequential processes with interactive concurrent design (Dong, Lam, Huang, & Dobbs, 2007). However, whilst integration is seen as desirable, it is proving elusive. Although proposed in the late nineties it has not happened to date.

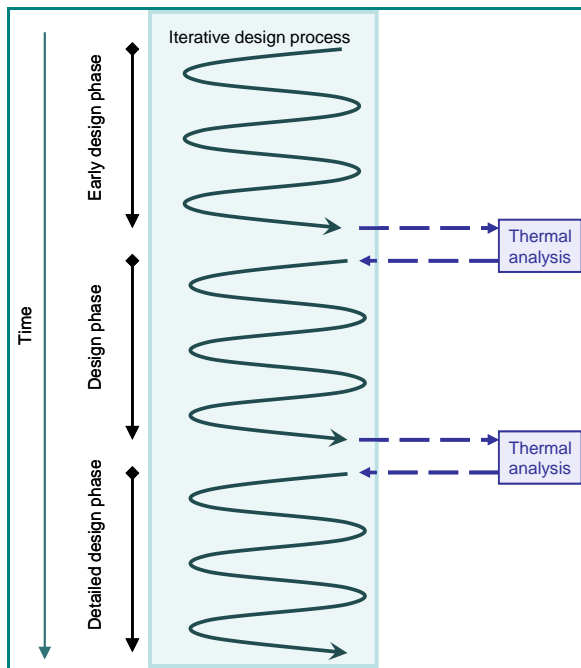


Figure 1 The design process over time, showing design as an iterative process with thermal analysis carried out as a separate process that interrupts the design flow

CASE STUDY

This section outlines a case study that investigates issues of designing buildings using simulation software by designers without the backing of extensive specialist support. The aim was to establish the deficiencies of employing current software in an iterative process, test attitudes to possible alternative approaches for improving software and to solicit any additional suggestions from the respondent.

An earlier survey carried out by Attia et al (2009) compared and evaluated ten BPS [Building Performance Simulation] tools. The survey investigated the usability of the interfaces and the integration of a knowledge-base. The survey reported here has a more narrow focus than that carried out by Attia et al, specifically looking at the process of designing a low energy building and feeding forward to how BPS and BIM software might be better designed.

Methodology

A judgment was made that architectural students would be a rich source of opinions in the context of this work. Judgment sampling is a common non-probability method (StatPac Inc, 2010). It can also be used in the initial stages of software requirements elicitation (Rogers, Sharp, & Preece, 2011). This was a non-probability sample, rather than a tool for population measurement of, for instance, the views of practising architects with varying levels of interest and experience. As a group, the students had all gained the same experience of a building study - to design a low carbon building which involved hands-on experience of the same environmental modelling software. The results were examined for internally consistent relationships pertaining to opinions of software requirements.

The study was conducted with architectural students in their final undergraduate year and on a taught MA programme at the School of Architecture at the University of Liverpool. The students were taking an elective module, "Modelling the Environmental Performance of Buildings" which indicates a concern with the issues and a desire to engage with the problem. These students will become practicing architects when low carbon/energy policies have become a legal requirement. In addition, as design students they should be able to apply design principles when providing opinions on how the software might be better designed.

The building study consisted of the design of a two storey accommodation block (motel). The study, involved investigating contrasting approaches to the design of a low energy building in two diverse climatic regions, Munich and Sydney. Ecotect, designed for use by architects, is generally considered as easier for designers to use than most alternatives (Crawley, Hand, Kummert, & Griffith, 2008) (Schlueter & Thesseling, 2009) (Attia et al., 2009). It was therefore chosen as the software for this study. Following the design exercise, a survey was employed to gather qualitative and quantitative data from the students.

Survey results

The survey was detailed with a total of 63 questions asked, consisting of a mix of closed, multiple choice and open, optional, response

questions. The results were analysed on responses from 52 students. The majority of the students [92%] spent over 20 minutes on the survey, with the average times spent being 41 minutes. In addition, there were positive, and at times lengthy, responses to the optional open questions. This suggests that the students took time to consider and answer the questions thoughtfully.

All of the students reported experience using at least one type of building design modelling software [100%] with many being able to use two or more [63%] and some three or more [29%]. In addition, the majority [81%] considered themselves to have average or above knowledge of low energy design before taking the module. The expertise reported validated the opinion that the students would be a an authoritative group from which to elicit opinions on requirements for software design, rather than practicing architects whose skills in using, and hence understanding, many of the principles in modelling software would be less uniform or guaranteed.

The software requirements, elicited from the students through the survey, for new software are given in Table 1. They were either confirmed through closed questions or deduced from responses to open questions and arranged into themes. Thematic analysis was used to analyse this qualitative data, (Braun & V. Clarke, 2006). It was employed to analyse the requirements elicited and report patterns (themes) to be used to guide future areas of research.

Discussion

The students generally found it difficult to achieve a low energy building, with almost half [44%] finding it 'Difficult' or 'Very difficult' and many [40%] 'Undecided'. The students also recognised that there might need to be a compromise between aesthetics and thermal performance. That is they understood that a better-looking building might have an associated energy penalty. Only a small proportion [20%] thought there would be no increase in energy usage if they tried to make the building more aesthetically pleasing, with over a quarter [27%] predicting a considerable increase.

This paper is concerned with the software requirements grouped within the theme of *Improved modelling*, shown in Table 1. There are a number of requirements that relate to integration and or better interoperability of design and simulation software. The consensus from the students [83%] was that the availability of thermal analysis software integrated with conventional 3D modelling software would be desirable to enable the design of aesthetically pleasing low energy buildings. They also agreed with the suggestion that it would improve the overall design process to have energy simulation functions integrated into standard design software (CAD or BIM) [92%], with only a few [8%] saying it would

make 'No improvement'. The next section discusses the barriers to such integration.

Table 1 Three themes deduced from requirements elicited from a survey of architectural students

THEME	SOFTWARE REQUIREMENTS
Improved modelling	Ability to move models between design and analysis software More intuitive modelling techniques as found in design software More complex 'realistic' models Using surfaces on the 3D model to identify areas of energy gains and losses Improved visualisation of materials in the 3D model. Combination of thermal simulation with design software Improved interoperability Improved visualisation of the building model
Visualisation of data	Values used in simulations to be made explicit Any data displayed should be done in an appropriate manner for a designer Methods to set and display an energy target Methods to calculate and display renewable energy sources Improved display of data, in particular, graphs Historical data to be recorded and recalled Display of multiple sets of data Help with explaining graphs Tracking of results as the design evolves Alternative visualisations to graphs
Design decision support and knowledge system	A need for a knowledge support system A need for calculation support Greater support in decision making with use of tools such as checklists, walkthrough guides and expert knowledge systems A database of high performance materials Help with error messages Help with explaining attributes or Local details; availability of materials and transport of materials to site

THE BARRIERS TO INTEGRATED SOFTWARE

Papamichael and Pal (Papamichael & Pal, 2002) cite the main barriers to the development and use of BPS tools to be the low market interest and high time-cost of applying them. The changes in legislation to mitigate climate change by the reduction in energy used by buildings may alter this situation. Clarke (2001) also lists barriers to the uptake of the application of simulation to the design

of the built environment. One software issue he outlines is the need for the development of suitable user interfaces to provide access to the considerable power of simulation. The next section discusses the limitations of current software and interoperable languages used to transfer data between BIM and BPS.

Current BIM and BPS software

Current design and simulation software tools are used in very different ways, involving parallel processes as shown in Figure 2. On the left hand side architectural tools are shown, these have been developed for use primarily by the architectural profession, with specialist CAD [Computer-Aided Design] or BIM [Building Information Modelling] software for associated professions, such as structural engineers, mechanical consultants, landscape architects. Only four BIM tools are listed on the Georgia Tech website specifically as ‘Design Tools’; Archicad, Vectorworks, Revit Building and Bentley Systems (Digital Building Lab, 2011).

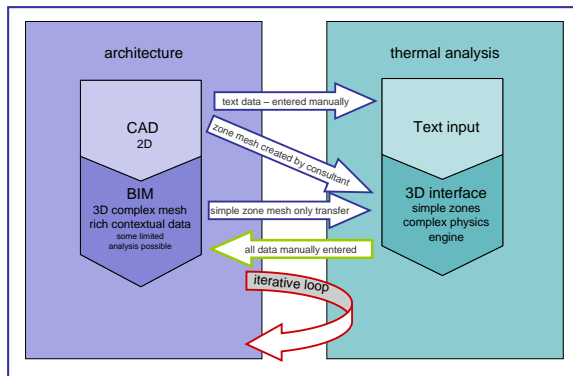


Figure 2 The parallel processes of architectural design and thermal analysis software showing the movement of data between the software. It is not currently possible to achieve an iterative design process between the types of software due to limited interoperability.

Thermal analysis tools, shown on the right hand side, have been developed for use primarily by energy experts to assess designs against standards/codes or to size mechanical plant. There is a plethora of building energy simulation programs available (at least 393 at the time of writing) with a wide range of analysis parameters such as building envelope, solar gain, day lighting, infiltration, ventilation, electrical systems and equipment, and HVAC [Heating, Ventilating, and Air Conditioning] (U.S. Department of Energy, 2011). Most of these tools have been developed by academics, researchers or HVAC engineers (Papamichael & Pal, 2002; Attia et al., 2009). In a comparison of 20 major programs Crawley et al. concluded that there was no common language to describe what the tools could do (Crawley et al., 2008).

Movement of data from design environments to analysis environments can take three forms as illustrated in Figure 2. It ranges from text (and numerical) input, 3D zone meshes created by the analyst based usually on 2D data and sometimes a 3D mesh. Even when a 3D mesh is exported from a BIM environment it requires visual checking for accuracy and frequently manual correction and cleanup (Krygiel & Nies, 2008; Bruning, 2011). It is not possible with current software to pass semantic data, such as building materials, with the mesh. If, as part of the thermal simulation to investigate the affect of different design options, changes are made to the 3D mesh or construction build-ups it is not possible to pass any data back to the design software after energy analysis. This lack of interoperability of data necessitates the manual entry of data and the resulting possibility of discrepancies and errors. The time involved also discourages iterative, holistic design practices (Eastman et al., 2011).

What are the problems with interoperability?

The main reason for the lack of data interoperability with BIM and BPS tools is that they generate building models differently and require different information. BIM software contains not only the building geometry and spatial relationship of building elements in 3D; it can also hold geographic information, quantities and properties of building components. Each component is an ‘intelligent object’ that is recorded in a backend database. The left hand image in Figure 3 shows a small, simple building partly ‘assembled’ with wall objects.

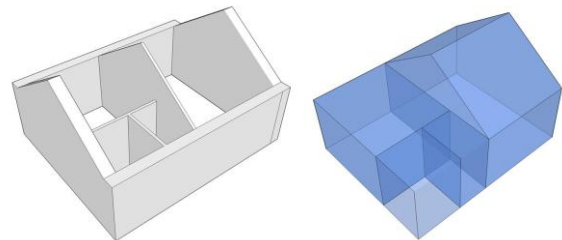


Figure 3 BIM software uses objects such as walls to make models of buildings as shown on the left. Thermal simulation uses zones, volumes of air in thermally consistent spaces, as shown on the right.

The main purpose of BPS is to model as closely as possible a real-world physical process. It is possible to construct a very thorough model that can simulate most of the complex interactions included in energy performance, but it requires huge attention to detail, so a simplified model is normally used. The basic concept employed in thermal calculations is the thermal zone for which internal temperatures and heating and cooling loads are calculated. Each zone should contain an enclosed volume of relatively homogeneous air. The right hand image in Figure 3 shows the same small building modelled as a series of zones.

Zone models are generally simple, for instance walls are treated as surfaces without thickness. A significant issue of preparing models for transfer between the different environments is where the boundary between zones lies: is it the centre-line or the inside face of a wall or floor? If the inside face is used there a false space can be created between the surfaces which can adversely affect the simulation (Steel et al., 2010; Bruning, 2011).

There is also concern as to the definition of the ‘thermal view’ of the building, or rather who creates the zones. Should it be the designer who knows the building well or a thermal expert who understands the physics better? Ultimately the result is likely to be arbitrary (Bazjanac, 2008). In our study of students using BSP software the majority found the creation of the zone model the least difficult task in the project [69%]. The majority of the students [77%] would however, like to be able to create and then export the zone model from conventional building modelling software.

Interoperable formats

Interoperability in the AEC [Architectural Engineering and Construction] field has traditionally relied on file-based exchange formats limited to geometry such as DXF [Drawing eXchange Format]. Data models. However, the need to include semantic data led to the development of IFC [Industry Foundation Classes]

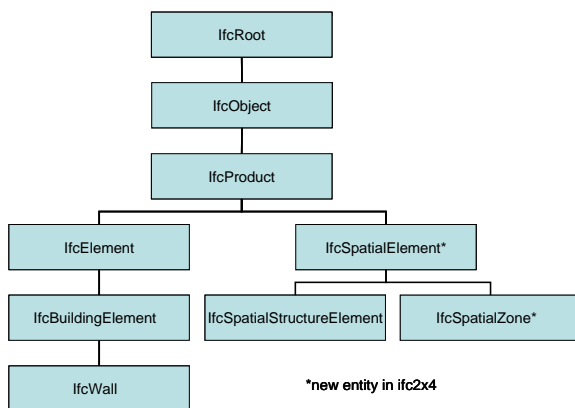


Figure 4 Showing part of the ifc2x4 hierarchy with new entities for Spatial Elements and Spatial Zones. A wall appears as an entity but inherits many attributes from IfcProduct.

The IFC schema was developed in the mid-nineties as a product data model for the design and full lifecycle record of buildings, by industry-led buildingSmart (formerly the International Alliance for Interoperability). Although it has broad support by the majority of software companies, the implementations are inconsistent (Eastman et al., 2011) (Grilo & Jardim-Goncalves, 2010). Software companies do not always support interoperable standards as their adoption can threaten the

maintenance of dominant market positions. There is concern that although BIM software companies are now developing suites of modelling and construction-related software with good data interchange within that suite of tools this does not extend to applications produced by competitors (Jardim-Goncalves & Grilo, 2010). The current standard is ifc2x3, with the next version, ifc2x4, coming to the end of its development phase (at the time of writing it is ifc2x4 Release Candidate 2). It should become the standard during 2011. The IFC model is both rich and highly redundant, offering different ways to define objects, relations and attributes (Venugopal et al., 2010). It has been developed to be generic, to meet the requirements of many factions in the AEC industry such as architects, engineers, contractors, suppliers, fabricators, government officials, etc. IFC is complex, reflecting the semantic richness of building systems. IFC2x4 has over 800 entities, 358 property sets and 12 data types (BuildingSMART International Ltd, 2011).

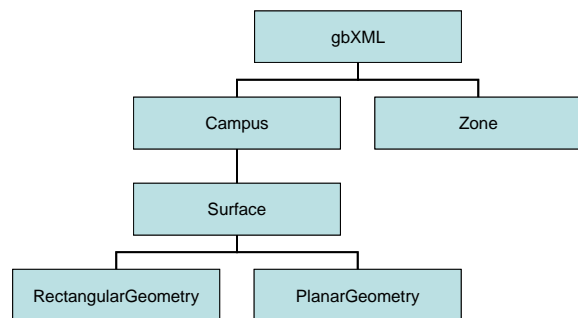


Figure 5 Showing part of the gbXML hierarchy: walls occur as an attribute of Surface as an enumerated type - either an InternalWall or ExternalWall.

Although the aim of IFC is to “Contribute to sustainable built environment through SMARTER information sharing and communication” (Rooth, 2010), exchange of thermal data is generally achieved by using a different language, gbXML [green building XML]. The gbXML schema was developed to transfer information needed for energy analysis (GbXML.org, 2010). The current version is 0.37 released in 2008. Again, like IFC, the implementation of the schema varies significantly, even though the schema is considerably less complex (Dong et al., 2007).

The two schemas handle data differently, which will partly explain the difficulties in creating translators between the two standards. Figure 4 is a hierarchical diagram of part of the IFC standard showing how a wall is defined as an IFC entity, IfcWall. The wall entity inherits attributes from all of its parent entities. The position of an instance of a wall is defined by the parent IfcProduct entity. Note that new entities IfcSpatialElement and IfcSpatialZone have been added to the IFC2x4

schema to facilitate storage of data relating to zones. There is no equivalent wall entity in gbXML, the closest item is an enumerated attribute of *Surface*; its position in the gbXML hierarchy is shown in Figure 5. This corresponds to the different methods of modeling illustrated in Figure 3, BIM models are composed of building objects and thermal models of zones with zero-thickness surfaces. The position and geometry of the surfaces in the zones are handled in the children entities of *RectangularGeometry* and *PlanarGeometry*.

The next section outlines our vision for new software and the resulting need for a change in hierarchy.

A PROPOSAL FOR A NEW HIERARCHY

To enable an iterative design process that includes regular assessment of the energy implications of design changes, existing modelling methods will need to change. This is not an easy process, if it was it would have happened by now. The vision is for design software to facilitate early massing models composed of zones. Our research with architectural students suggests that building designers will find this relatively easy. The creation of zone models by building designers for thermal simulation is not new. For example it was employed by Marsh with the development of Ecotect (Marsh, 2006). Where this proposal varies from Ecotect, is that the zone model acts as a basis for BIM modelling. Figure 6 illustrates this concept. The left hand set of images shows how a small building, consisting of objects, acts as a container for zones. This is the method used at present by BIM software to generate zone data. The problems with working with this method is the computational derivation of zones can be inaccurate and requires manual checking for accuracy (Krygiel & Nies, 2008). Also, it has proved impossible to date to facilitate the conversion of zone geometry back to the object form employed by BIM.

The right hand side of Figure 6 shows the same building assembled as a series of zones, with the enclosing objects ‘stuck’ onto the zones. The zone would then act in a similar manner to an ‘elastic band’ shrinking or expanding as changes are made to the walls or floors. Whilst this could probably be achieved with the existing IFC hierarchy, we propose a much tighter inheritance approach. with the enclosing elements such as walls, floors and roofs added afterwards.

This is akin to the rule based approach demonstrated by Farrimond and Hetherington (2005, 2006) in the development of software to model church buildings. Analysis of the architectural style of traditional English churches revealed that their major components can be classified as variations of an underlying type which was called *room*. The nave, chancel, transepts and towers can all be regarded as

room type objects. Instead of the *room* type object we propose that the *zone* type is the major component or building block as illustrated in Figure 6.

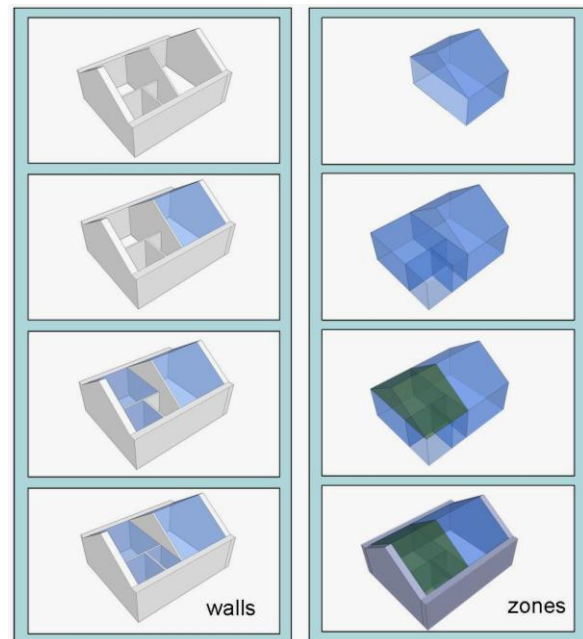


Figure 6 Showing on the left how a model as a building is made using objects such as walls and the zones added afterward. The illustration on the right shows how the building could be built up with zones

Eastman et al. (2011) discuss the implementation of technological interoperable frameworks by computer scientists through the development of languages such as EXPRESS (the basis for IFC) and XML. They argue that knowledge experts, such as architects, could be better at defining the content of information exchange – “*user-defined exchange standards seem an imperative*” (Eastman et al., 2011). The IFC model, however, has been designed to be abstract, to enable it to be used with multiple applications (Khemlani, 2004). The data model specifies relationships that are associated with entities rather than relying on inheritance. For example an instance of a wall would be placed in a model of a building using an *IfcProduct* as shown in Figure 4 and associated to a thermal zone by use of *IfcSpatialStructuralElement* and the relationship *IfcRelContainedInSpatialStructure*. This reflects the current situation with BIM software of ‘retro-fitting’ zones to the building model.

To support the proposed modelling technique illustrated in Figure 6, a change to the IFC schema is suggested which would give the zone volume more significance. Figure 7 shows our suggested change to the structure. The *IfcSpatialElement* is moved higher up the hierarchy to enable the *IfcProduct* entity to inherit geometries and position. This would mean much tighter coupling of the zone and the building objects. Our software vision includes the ability to ‘turn off details’ or facilitate filtering, so

that the details of the BIM model can be hidden, leaving the zone conceptual model. This would be considerably easier with the software data arranged in the hierarchical structure proposed. This, we believe, would make it easier for the iterative use of the building model with thermal simulation within the design software environment.

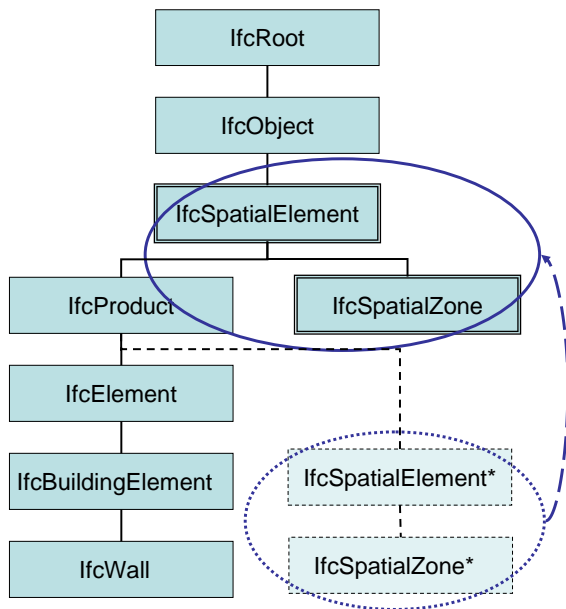


Figure 7 Shows how the IFC hierarchy could be re-arranged with IfcSpatialElement moved above IfcProduct to enable inheritance of attributes.

CONCLUSIONS

A vision for architectural design software based upon thermal zone modelling has been presented. This method could be a key to the integration of BPS and BIM software. This could facilitate the more widespread application of thermal simulation by small architectural practices, driven by legislation, to design very low energy buildings. Integrated software could support the iterative and holistic processes necessary to design healthy and aesthetically pleasing as well as technically rigorous buildings.

Whilst not totally dependant upon the restructuring of interoperable standards, the inheritance in the proposed hierarchy would make it considerably more elegant and arguably provide more reliable interoperability. Whilst accepting that a considerable effort has been put into the development of current standards, we believe the structure of the 2x4 version inhibits the transfer of model details between BIM and BPS software. A limitation of this proposal is that it will force architects to design with zones in the early design stage, but our survey of architectural students has shown that this should not be a problem. We would also argue that this will be necessary as legislation and practices move towards the requirement of new

buildings designed to rigorous, maybe even draconian, energy standards.

Although this paper has suggested a different hierarchy for interoperable languages, it has dealt lightly with many of the details. For instance, what geometric and positioning attributes need to be provided to enable implementation of both BIM and BRS operations? BSP software requires many more input parameters, how would these be handled in an altered IFC? These all represent topics for future work. This proposed change in the hierarchy should not affect other elements of the standard, but again verification of this requires further work.

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