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Using 3D CAD modelling to support coordination of building systems

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15.1 Introduction

Buildings are constructed to serve the needs of their occupants. Occupants need facilities with comfortable, safe and healthy environments, utilities and technical equipments to perform their work. Building systems may be defined as a group of electro-mechanical components connected by suitable pathways for the transmission of energy, materials or information and directed to a specific purpose. An integrated approach to building systems gives consideration to the overall objectives rather than the individual elements, components and subsystems.

Traditionally, coordination of building systems is primarily between mechanical and electrical engineers that is passed down the line to contractors to coordinate on site. In the past two decades the integration of diverse technologies such as mechanical, electrical, bioclimatology, geophysics, optics, electronics and computer engineering plays an important role in the design of building systems and the environment they control. Building systems applications may include heating, ventilation, air conditioning, and cooling (HVAC); lighting; power; security; fire and life safety; building automation; audiovisual communications and computer networking of various kinds. Because of the large number of interrelated factors in these systems, there can be many solutions to the same building problem, all of which will satisfy the minimum requirements (Ahuja, 1997).

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The computerisation and integration of building systems technology and the information age we live in have changed the way humans perceive their habitat. Computers are mathematical instruments of enormous value in the science of building systems design. Computer-aided design (CAD) systems are extremely valuable tools in drafting and modelling. This chapter introduces 3D CAD modelling as a tool to support the coordination of building systems in designing, construction and maintenance.

15.2 Using CAD modelling in building systems

In earlier times wherein computers were not yet developed, there has been a representation of using conventional media in designing. Ancient architects used text to abstractly describe the design process (Hewitt, 1985). 2D drawings were later introduced and only expressed abstract visual thinking. Then with the massive use of physical models in the Renaissance, the form of space and architecture was given better precision. The attempts have been continued to identify the nature of different design tools.

On recent years, digital technology has been developed and matured at an unprecedented rate. This growth has led to a converging phenomenon that erodes the traditional boundaries of computing. Compared with conventional design media it is worth employing computer technology meaningfully to bring significant changes in the process of building systems design and maintenance. The conventional approach involves the use of drawings and models as means of representing the basic convention. The type of models used in the design process can either be a physical or digital model. Both types were used as a means of solving complex problems that 2D drawings were unable to handle (Lin, 2001).

3D building models are useful across the entire spectrum of architecture, engineering and construction (AEC) practices. Architects and their clients use 3D building models to observe and evaluate building designs before construction, while there is still chance to make substantial changes at a reasonable cost. Engineers use 3D building models for energy, lighting, acoustics and fire simulations. The results of these simulations give valuable insight into building useability and safety. Professionals in the construction industry utilise 3D models to estimate costs and to plan cost-effective construction sequences. This process often leads to early discovery of design conflicts that would otherwise result in expensive construction mistakes. Even for an existing building, it is often desirable to have a 3D models to analyse the energy properties of the building or to explore how a potential fire might spread to study potential changes to the building, or to study possible uses of existing building spaces (Lewis and Sequin, 1998).

Drafting is still associated with the common perception of the application of CAD to architectural design. CAD technology has progressed to a level in which it is possible to communicate design expressions representing early stage design ideas right through to detail drawings. This is quite different from CAD as an instrument for efficient production, or as a vehicle for the graphic presentation of the already designed building. Being able to use 3D CAD systems fluently is synonymous with being a good designer, rather than a draftsman (Szalapaj, 2001).

15.2.1 What are 3D CAD Models?

3D CAD models are three-dimensional computational representations of objects drawn in the x, y and z axes and illustrated in isometric, perspective or axonometric views. These views are achieved simply by rotating the viewpoint of the object. A 3D CAD model of an object in general provides the following advantages: (a) an object can be drawn once and then can be viewed and plotted from any angle; (b) A 3D CAD object holds mathematical information that can be used in engineering analysis, such as finite-element analysis and computer numerical control technology; and (c) A 3D CAD object can be shaded, rendered and assigned various materials for visualisation. 3D CAD models can be generated by the use of various types of CAD software systems such as AutoCAD, Microstation, ArchiCAD and many more.

15.2.2 The role of 3D CAD models in design and construction

An understanding of the ways in which 3D CAD modelling techniques can be used to support and reflect design thinking, can then lead to the development of a greater integration in the building design and construction industry. Since the inception of CAD, computers appear to have played a vital role in the practice of architecture, engineering and their allied profession. This however, is merely an illusion. This simply did not happen because most designers in practice were not formally trained to use the computer as a productivity tool, they are unfamiliar with its capabilities. In fact, this practice still utilises designers who develop conceptual sketches for a project, then these sketches are passed on to draftsperson who create 2D design development and construction document drawings of little integration, if any, with other building or discipline consultants.

The primary purpose of a 3D CAD model needs to be established at early stages in a project. 3D CAD modelling can be used in structural, lighting, acoustic, thermal, acoustic, bio-climatic and spatial analysis. This Chapter is not intended to cover all of these important issues but rather to focus on the use of 3D CAD modelling to support the coordination of building systems. A common misconception of CAD systems is still as drafting tools in the post-design stages of work rather than playing a much more richer role in designing and construction. 3D CAD models could help to resolve ambiguities, provide linkage to design data and present computerised visualisation.

The cost of an early discovery of design conflicts and inconsistencies is far less compared to the cost of repairing design and construction mistakes in buildings that increases exponentially at every stage form conceptual design to construction operation as shown in Fig 15.1. 3D CAD modelling allows for such inconsistencies to be discovered and for better design and construction decisions to be made at the very early stages.

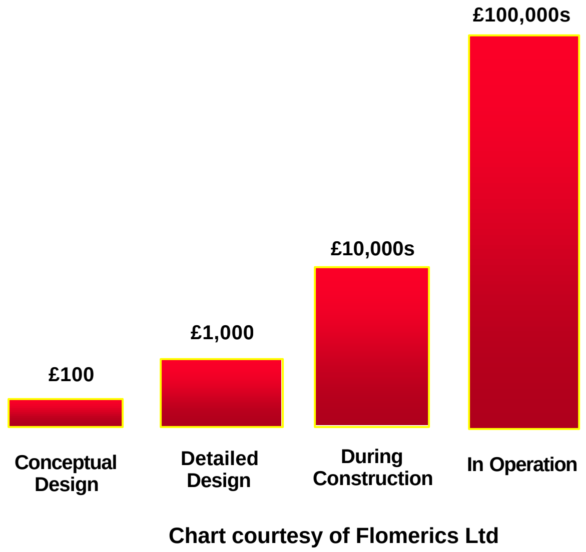


Fig. 15.1 Exponential increase in repairing design and construction mistakes from conceptual design to construction operation.

15.2.3 Interoperability and data sharing of 3D CAD models

Interoperability has one important meaning that is the capability of devices of different manufacturers to communicate and work together. This meaning has great appeal and benefits, but it can never be used against improved and more elaborate designs of transmitters and hosts.

The lack of efficient interoperability of 3D CAD modelling is arguably the single largest software problem facing today's manufacturers. It can cause time-to-market delays, bottlenecks, errors, lost data, quality problems, and extensive reworking of parts. This problem also impedes the cost-effective outsourcing of design and production in global manufacturing.

There are currently various software designed to facilitate interoperability among manufacturers and suppliers. They assist in converting and viewing CAD formats; translating between many different CAD/CAM (computer aided manufacturing) formats; and modifying and sharing objects. Moreover, there are Application Service Providers for the translation and healing of 3D solid models, enabling rapid sharing of 3D engineering data across design and manufacturing firms, and their clientele, regardless of their installed CAD systems.

15.3 Advantages of using 3D CAD modelling in building design and construction

The advantages of 3D CAD modelling cover the whole plant-life from layout and design to construction and maintenance. The development of 3D CAD software systems has enabled planning procedures to be changed from 2D for each engineering discipline (piping, wiring, HVAC, etc.) to an integrated 3D planning procedure. 3D CAD modelling encourages users to plan work thoroughly to create their documents. After a 3D model of the building structure has been built from architectural and structural drawings, the main internal equipment is added. The draft arrangements of the different engineering disciplines determine the allocation of the available space and planning can start. Since a designer from one discipline can see the results of the other disciplines' work, a visual collision check is performed during the planning procedures. The visual collision check is currently carried out via a walkthrough inside and around the 3D CAD model. When planning is finished for the rooms involved, an automatic collision check is performed, which normally a handful of collisions to be eliminated. Further modifications, desired by the project manager or client for example, can be accounted for (Lockau, 1996).

3D geometric CAD models usually are in the form of wire frame and solid modelling. Wire frame modelling, still widely used by architects, is known as the ancestor of contemporary CAD presentation. The nature of wire frame models reveals the underlying structure of the building, thus helping architects check the project's buildability. Due to this ability, wire frame modelling is used for establishing the building's skeleton in the developmental design stages of most CAD programs. Solid modelling is usually utilised for the finished model. Despite wire frame modelling's advantages, some architects prefer using solid modelling in the primary stages as well as in the final stage. The difference between wire frames and solid modelling is parallel to the difference between using paper/pencil and a 3D object like wood or foam to construct the initial design. Even if solid modelling is used from beginning to end, the first draft does not look remotely like the finished design. In the early stages, the architect is not interested in making the building look realistic, only in outlining the rationale of the design. The importance of the computer is as an interface between the physical design and the abstract ideas behind it. It the later stage of design, realistic elements, like colour, lighting, and shadows, are added to help communicate the building design to the client.

3D CAD integrated systems such as Architectural Desktop and Microstation Building Plant and Engineering enable the designer to seamlessly integrate mechanical and electrical design within the building structure. This allows exchanging accurate design information with other industry professionals. With the addition of Internet capabilities, this provides the designer with the ability to leverage this power in order to enhance coordination among the entire design and construction team. This will help in reducing design cycle time while offering useful tools for design and construction documentation. Furthermore, scheduling information and space planning data can be extracted and exported to external databases for further analysis to assist building owners in post-construction facilities planning and management. It enables facilities managers to track room square footage, maintain assets like furniture and equipment, track asset quantity and cost, and export this data to external databases for reports.

From a coordinated 3D CAD model, individual services layouts can be generated for example ductwork, mechanical pipe work, public health, fire protection and electrical services using relevant layers with text and dimensioning. These can be output for accurate tender pricing, and the on coming Contractor can use the full coordinated drawings for installation purposes. The resultant model can be utilised for external and internal visualisation and animation, thermal calculation, lighting design, sun studies and crowd evacuation.

These are coordinated within the prototype and continuously tested for clashes and discrepancies. Fully coordinated construction drawings are produced directly from this model. This will shorten the overall design coordination period, identifies construction problems within the computer, thus saving time and money, improves productivity and reduces defects on site.

15.4 Using 3D CAD Modelling as a means of useful knowledge sharing

Building design is a process that often been considered as an activity carried out by architects and engineers. They are co-designers in proposing the end product of a building form, materials, supporting structure and environmental control services. However co-designers share the same task, that is designing a specific building, they seem to think rationally about concepts with regard to their own particular interest in the evolving building solution. Their co-designing work is in the form of knowledge contribution from each of them based on their particular experience. Their method of working together will therefore be in the form of knowledge sharing in order to evolve a commonly agreed building solution. Knowledge sharing by each of the co-designers can only occur particularly if they can exchange design information which will present the output and input to their individual knowledge contribution (Cornick, 1996). Example of the knowledge shared among the co-designers include: shapes, proportions, arrangements, and materials of building element brought together in an overall building form; structural and services elements and enclosures with regard to their structural stability; and size, shape and arrangement of building services.

The development of a 3D CAD model has an essential role to support the knowledge sharing among co-designers. One set of designers conceive the overall form and how all its parts would fit and work together, other designers conceive how all the system parts can be engineered as an overall assembly. The degree of realism that can be created in the 3D CAD model and the ease by which 3D views can be generated are essential in knowledge sharing. This is a much richer notion than demonstrating the material finish and form of building objects.

15.5 Object oriented approach for 3D CAD modelling

The representation of building objects is not limited to the graphical information that illustrates only the structure of these objects. There are various other types of non-graphical information that are not less important than the structural representation of these objects. Non-graphical information includes functional, behavioural and semantic properties. Each building object is created to perform certain functions. These functions should produce the required set of behaviours. An integrated view of both graphical and non-graphical information can be looked at as functional, behavioural and structural scheme of object representation. The structure is “what is”, behaviour “how does” and function “what does”. Furthermore, the purpose of creating this object or building element is “how does” or “what for”. The structure of an object exhibits behaviour; behaviour effects function; and function enables purpose. The purpose of creating an object is enabled by function; function is achieved by behaviour; and behaviour is exhibited by structure (Rosenman and Gero, 1998). For instance, the of structure a hydraulic elevator includes piston and oil column; its functions are to contain loads and move them vertically; its behaviours are to push load up and holds by compression; and its purpose involves transferring people and goods from one storey to the other. The non-graphical information is not limited only to the description and properties of the object but also include the relationships of this object to other objects in the building. This is a simplified description of non-graphical information of an object or a building element.

The ability to exchange non-graphical information in building projects using the computer is quite useful. A general approach has been developed by employing computer techniques that were first applied in the field of artificial intelligence (AI). This approach encompasses objects that have attributes, one of which is their geometry which can be viewed by CAD systems; databases that contain non-geometric attribute description of objects; and data-structures that follow agreed standards and information. Linked computer systems would assist in describing the geometry of architectural form, the geometry of structural frame, the structural calculations of the frame, and the work sequence and time duration of construction. Using the AI approach, when the architectural form (graphical information) is changed the other three systems (graphical and non-graphical) automatically change to suit the new form. The importance of this approach lies on the capability of computer systems to recognise the graphically represented objects as real objects with attributes rather than just geometrical forms. Object-oriented databases incorporated within CAD systems allow of such a facility to be utilised. Also, object-oriented technologies facilitate the support of collaborative design.

CAD systems are now becoming increasingly object based and similarly web-based systems are moving in a similar direction. Recent trends in CAD systems development (Szalapaj, 2001) attempts to integrate GIS (geographic information systems) with facilities management. This type of development involves making connections between graphical and non-graphical information and object-oriented environments for supporting such integration are increasingly being used. The integration of graphical and non-graphical information is of paramount importance in achieving high results in planning and co-ordinating building systems.

Object-oriented computer-aided design is an important new development in the architecture and engineering professions. Traditional CAD systems were developed to mimic the processes of hand drafting and overlay graphics. A traditional CAD drawing has little more intelligence than a hand drafted paper document. Object-oriented computer-aided design represents the next generation of CAD applications predicated on the concepts of object-oriented design that has been used successfully in the software industry to build vastly larger, more complex applications than were ever-possible using older design methods. It is only recently that object-oriented design has been applied as a way to conceptualise and communicate design problems.

The development of new CAD systems will lead architectural and engineering practices to change their working practices in redefining the boundaries of CAD systems in the course of their applications to real projects.

15.6 3D CAD Modelling supports co-ordination

Paper-based presentations (drawings) of building design and construction documentation have been the conventional method used for coordination between the disciplines of the building industry. These drawings whether done manually or computerised only contain unstructured graphic entities such as lines, text notations, dimensions and symbols. Through agreed conventions between various disciplines these graphic entities are interpreted as a coherent set of documentation from which the building could be comprehended and constructed. Any inconsistencies between the various buildings systems, such as structural, mechanical, electrical, HVAC and security have to be discovered and corrected. This is usually done by marking the appropriate drawings and sending them back to the appropriate discipline. It is a very challenging process that needs full understanding, imagination and visualisation capacity from a coordination team to discover the inconsistencies since all drawing are projected in 2D format. The third dimension needs to be constructed and visualised in the mind of coordination team members.

Creating 3D CAD models from the ground up using architect's drawings and including structural and services makes sure if they all fit. This necessities that building systems specialists should be on board preferably at the schematic design stage to play their roles as co-designers. 3D CAD modelling could deliver significant productivity improvements if applied early enough in a project. It is much cheaper to rub it out on a drawing than to sort it out on site. Coordination of building systems does not mean that every thing is down to the building contractors. Most of construction disputes centre on time and information. When the contractor finds things do not fit, arguments starts over responsibilities, the contractor does not want to do it and the whole thing collapses. Building systems are the most crucial area of coordination and are always the biggest hassle especially with complex buildings such as hospitals. If the design and construction industry commits itself to a complete 3D CAD modelling, at least 30% savings is going to be made by getting the coordination right before the start on site (BSS, 1997). One of the corner stones to achieve efficient coordination is to clear out the ambiguity of design objects and this can be easily done using 3D CAD modelling as shown in Fig. 15.2. 3D CAD models could be rendered and shaded as shown in Fig 15.2 or could be in the form of extract line drawing as shown in Fig. 15.3.

Fig. 15.2 3D CAD modelling helps in eliminating ambiguities that may creep around in 2D drawings (BSS, 1997)

15.7 Sharing a 3D CAD model among various disciplines

The 3D CAD model can be organised so that each design or construction discipline has the ability for read and write access in the computer for its own planning work, whereas all the other disciplines have read-only access to its data. This allows every discipline to carry out draft planning and to examine planning options without interfering with the other disciplines.

The link between architectural 3D CAD models and building systems provides the opportunity to interrogate room objects to volumes and calculations. Sharing 3D CAD models helps to transfer performance information within the integrated design process. The transfer is not limited to graphical information but could be extend to non-graphical information to be linked to the 3D CAD model.

Sharing the 3D CAD model and having related disciples information available allows for generating cost-related components, material quantity and specification values in order to simultaneously evaluate whether the client's capital construction and facility-running cost requirements are being met.

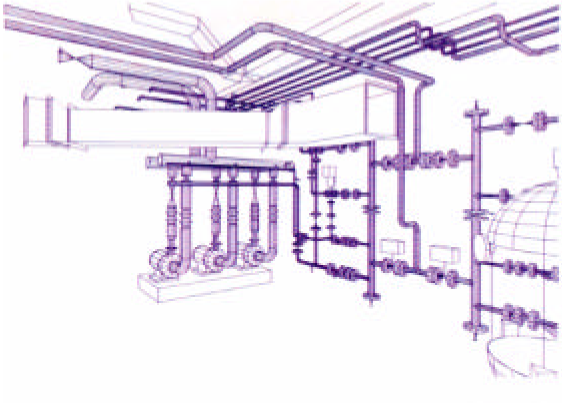
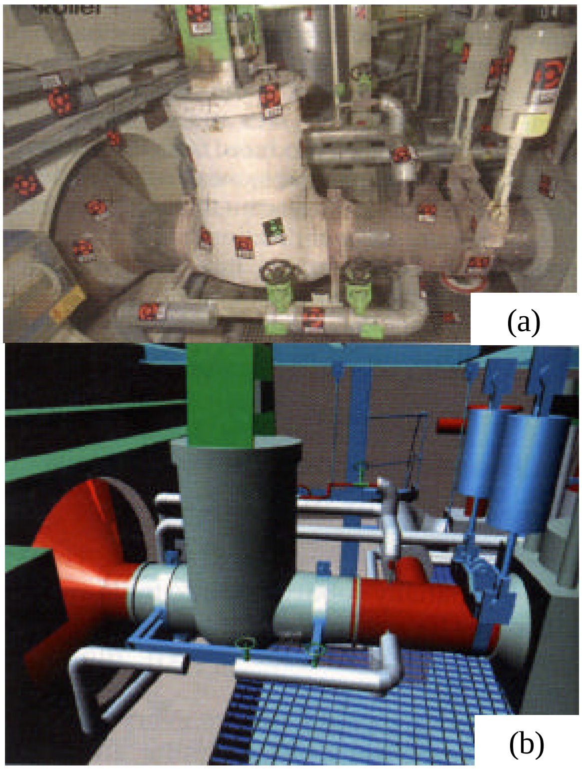


Fig. 15.3 3D CAD modelling presented in an extract line drawing

15.8 3D CAD modelling for building systems maintenance

The maintenance and reconstruction of building systems is as important as designing new systems. Reconstruction work starts, from the design point of view, with measurement and analysis of the existing situation. As-built information can be taken from the existing as long as it is available. In cases where the value of documentation has been worn away, photogrammetry with direct transfer of results into 3D CAD models can be very helpful. Photogrammetry is the technique of measuring objects (2D or 3D) from photogrammes. We say commonly photographs, but it may be also imagery stored electronically on tape or disk taken by video or digital cameras or radiation sensors such as scanners. Its most important feature is the fact, that the objects are measured without being touched. Therefore, the term remote sensing is used interchangeably with photogrammetry. Remote sensing was originally confined to working with aerial photographs and satellite images. Today, it includes also photogrammetry, although it is still associated rather with image interpretation.

For instance valve environments are often extremely congested, so a transport study is needed to prove that the clearance needed is available. In a real life example (Lockau, 1996), the worst case of a new valve with the largest height left an anticipated clearance of just 1cm. Consequently a picture was taken on the site as shown in Fig. 15.4(a) and a 3D CAD model is generated as shown in Fig. 15.4(b) to study different alternatives. The advantage of facilitating a 3D CAD model is manifested in this example wherein various alternatives can be considered to achieve the best solution in coordination with the adjacent equipments.



(a)

(b)

Fig. 15.4 (a) A picture taken on site and (b) a 3D CAD model developed from photogrammetry to study various solution alternatives

15.9 4D CAD modelling for effective facility management

A 4D CAD model is a 3D plus time. 4D CAD models allow the project team to visualise several what-if scenarios to ferret out conflicts before the commencement of a project. This reveals visible scheduling inconsistencies that might otherwise remain hidden in a sea of data until an on-site conflict surfaced. Communicating schedule details to subcontractors is one of the main benefits of using 4D CAD models. It is important to involve subcontractors early on in the project, show them the models and have it become a real collaborative process to have the teambuilding emerge. For instance, Fig. 15.5 shows a 4D CAD model that found safety conflicts. This scene shows steel being erected over workers laying metal deck on the Walt Disney Concert Hall (Homepage).

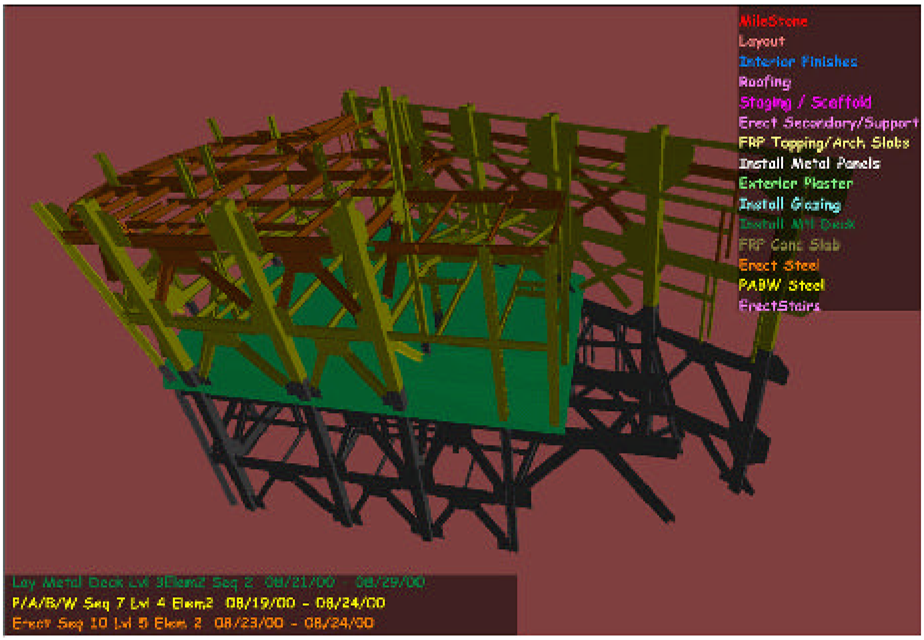


Fig. 15.5 Safety conflicts discovered by a 4D CAD model wherein steel being erected over workers laying metal deck on the Walt Disney Concert Hall (Homepage).

15.10 Intelligent 3D CAD objects

Current CAD systems are being widely used in the architectural design process, but as yet offer only limited benefits compared to their potential development. The fundamental shortcoming of current CAD systems in the early design tasks is that a graphical CAD drawing does not represent specific technical design knowledge. It does not allow the correct and full representation, interpretation and evaluation of building systems. Also, there has been limited development in the use of CAD systems as integrated design environments with sufficient cross-discipline information and knowledge. This shortcoming could be overcome by the implementation of more advanced CAD systems that could capture the "know what" (information), and "know how" (procedures) of the design. This is what could be provided by the knowledge-based engineering (KBE) approach (Hew et al, 2001).

The KBE is a promising AI technique yielding the following capabilities within a system: knowledge representation capability, reasoning mechanism capability and interface capability. Knowledge representation capability is about controlling design knowledge through modelling. Object-oriented expression and natural language rule expression are used to describe the expert knowledge. It can also sometimes be referred to as a rule-based system. In addition, the KBE system is concerned with intelligent inferences and facilities. Reasoning mechanism capability deals with searching for and selecting application rules and with evaluating and generating logical arguments using objects. The reasoning process is often conditional involving statements in the form 'if A then B else C', where A, B, and C are propositions. The reasoning process is proceeded by a repetitive sequence of message passing from one object to another. The execution of the application rules is invoked by the message received. A dynamic co-operative reasoning mechanism, as a means of communication between systems, is used to allow control of massive volumes of knowledge. KBE offers a sophisticated development environment for the developer to program the knowledge-based objects. It includes a knowledge editor, knowledge browser and a knowledge tailor. These functions offer the modeller a facility for editing and debugging the knowledge-base system (Hew et al, 2001).

Intelligent 3D CAD objects have far promising potentials for the next generation of CAD systems to be more useful and supportive for automated coordination of building systems. Intelligent 3D CAD objects can be roughly described as a 3D CAD system employing intelligent objects that can take messages and respond to them. In other words, intelligent 3D CAD objects know "what they are" and "what they can do" and used as a representation unit to construct a building system. An example of an intelligent 3D CAD object is a cable tray that knows its function is to distribute electric cables to various levels of the building and can be designed in a way that allows for abrupt changes in both vertical and horizontal directions and that there are certain distances need to be maintained between the cables and the distance separating the cable tray from what is below, etc. These active objects may be called agents that constitute the integrated building design systems.

These intelligent agents "objects" would allow for better collaborative and coordination among the disciplines of building industry and assist is discovering any inconsistencies at the time of design and prior to construction. Each intelligent agent "object" accommodates both graphical and non-graphical information. When an object is manipulated, corresponding effects will be made in all related objects in the building systems. If the update were not possible, at the very least some form of alert would occur to inform the related disciplines of a current problem that needs to be addressed due to the change from another or the same discipline.

15.11 Discussion

This chapter demonstrated the potentials for utilising 3D CAD modelling in integrating various disciplines of the building industry to assist in the coordination of building services and systems. Before this approach to be applied there needs to be a change in the procurement and management of the building project process.

Design and construction practitioners are becoming more involved in the use and development of leading-edge CAD systems. The utilisation of 3D CAD modelling and object-oriented modelling will lead to a greater efficiency in working practices between architects, structural, mechanical, electrical and civil engineers. This change must affect the roles of the disciplines involved and the relationships between them. The main aspect of this change should be that every discipline members involved should see themselves and seen by others as design partners or co-designers. If the building project design process is to be beneficially integrated then every one needs to be at the same mind about the final product solution. The essential role that 3D CAD systems will play in achieving this end will be through providing the capability for simultaneously processing and more importantly simultaneously presenting, the many different and varied information aspects of evolving building design solutions. The 3D CAD modelling will therefore continue to provide the visualisation medium and also be a powerful front end and information integrating mechanism by which the knowledge of each participating designer can be brought together to produce an greed, workable and coordinated design solution (Cornick, 1996).

By utilising the use of an integrated 3D CAD model, architects will go on designing building forms and materials and will be able to better demonstrate the all-round consequences of alternative proposals. Engineers will go on designing the structure and services to support architectural forms and will be in a better position to integrate their proposed solutions with those of architect's for coordination appraisal and verification. Construction managers will be able to design and manage production systems for construction as an integral part to the architect's and engineer's building solution design process. Specialist trade contractors will apply their particular specialist rules for effective, efficient and economic design.

Integrated building design systems with or without CAD is only possible through the forms of procurement and management that will encourage the equal involvement of all project participant designers during the building design process itself. The 3D integrated CAD modelling approach presented in this Chapter would be the most ideal of all, if the most satisfying building solution for a client's project were to be realised.

3D CAD models in building systems design need to be assessed not in terms of their quality of presentation but as objects with which to carry precise analytical and coordination functions. Full understanding of the ways in which 3D CAD modelling techniques can be utilised would direct the development of building designs systems from conception to completion. While architecture and buildings we inhabit are very much a 3D experience, design practitioners seem to be reluctant to venture themselves into 3D, often due to its perceived complexity.

Designers and engineers would need to use the computers at the outset to begin the thought process in a 3D form. This will have a great impact on the level of coordination required in designing and constructing building systems. Design and engineering practices operating in a non-integrated manner will not begin to realise true benefits until there is a complete change in the thinking process about technology and its place in their practices. 3D CAD modelling is an example of a computer technology that intends to make the design and construction practices more efficient and integrated. Specially in achieving an efficient and high-end coordination of building systems, 3D CAD modelling is an indispensable tool to use.

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