Expert Systems Integrated with CAD for Component Assembly

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ABSTRACT

The advent of the computer and its application to the process of building design led many to believe that some degree of automation would be possible for creating design solutions from prioritisised design criteria. However, there are two major problems involved in modelling the 'whole building' design process. Firstly, the design process is rarely explicit and secondly, acquiring and representing the symbolic and semantic task.

This paper considers the architecture of knowledge-based design systems currently in use within the construction industry. Two example systems are described. Following on from this we examine the possibility of multiple knowledge-base systems for whole building design.

This paper believes that simply interfacing existing uni-knowledge-based system will not provide a feasible architecture for a multiple knowledge-base system. An alternative methodology is presented, whereby a single coordinated construction model is used as the central element of the system. This model will provide coordination between knowledge-bases, while also being a complete geometrical and functional description of the building.

Finally, the role of computer-aided draughting systems are considered in relationship to the suggested multiple knowledge-base architecture and the structure/protocol of the coordinated construction is suggested as a basis for graphical and non-graphical data exchange.

INTRODUCTION

The advent of the computer and its application to the process of building design led many to believe that some degree of automation would be possible for creating design solutions from prioritisised ed design criteria (Broadbent 1973, Patterson 1980). However, there are two major problems involved in modelling the 'whole building' design process. Firstly, the design process is rarely explicit (Lawson 1980) and secondly, acquiring and representing the 'world knowledge' required by the computer system presents a formidable symbolic and semantic task (Bijl 1985).

The gradual uptake of computer-based system in building practice has been much more modest than these researcher's had envisaged. Computer-Aided Draughting (CADr) is used merely to visually portray a building design once it has been proposed by a human designer and automatically calculate some of the functional and resource requirements (Atkin 1987). It is suggested therefore (Cornick 1987), that to use computers as design aids rather than only draughting aids is to accept that:

- the human designer proposes the geometric form
- the computer is used to rapidly asses the proposed form against detailed performance and production criteria

The above approach to Computer-Aided Design (CADn) is possible because the nature of building technology is such that a variety of specific domains of knowledge are required to form its general knowledge base (e.g. component assembly systems for various building elements, spatial relationships, energy consumption etc.). AI computer programming techniques allow modelling of the reasoning 'rules' of which this domain specific knowledge is a class.

In human-aided design all of the knowledge domains are brought together within the mind of the designer at a relatively superficial level during scheme design (i.e. he/she makes conceptual connections between 'rules' for partitioning, brickwork, structures etc. in proposing the outline building form). Selected models of the design (sets of annotated drawings, mathematical models etc.) are then passed from specialist to specialist, each of whom applies his/her detailed experise. However, at all times the actual design - the complete concept of the building - is known only to the designer. The essential problems therefore, if CADn is really to be achieved are:

- defining the fundamental model of a building known to the designer
- examining the other models to which the specialist domains of knowledge relate
- understanding how the various specialist knowledge domains interact

Integration of knowledge bases with computer graphics is currently being developed for domains such as eaves detailing (Radford 1986), kitchen layout (Baykan and Fox 1986), apartment layout (Ma´rkusz 1982) and high rise structures (Maher 1985). This paper will further describe two other similar research projects for brickwork cladding (Bowen, Cornick and Bull 1985) and internal dry wall partitioning (Cornick and Bull 1987). The remainder of this paper will consider how these knowledge-based system can be integrate, with reference to the architecture of a 'multiple knowledge-base system' and in particular the model of the proposed building design used as the basis for such a system. Finally, the implications for CADr systems and their role within the multiple knowledge-base system will be examined.

THE ARCHITECTURE OF A UNI-KNOWLEDGE-BASE DESIGN SYSTEMS AND TWO EXAMPLES

Traditionally, Knowledge-Based Systems (KBS) in general and in particular those concerned with the construction industry, can be said to comprise three characteristic parts (see figure i).

- The Construction Model (CM): Inside every KBS is a model that describes the building currently under investigation. The model is usually created from empty data-structures, which are instantiated by either the user, while he/she is providing information about the construction or by the KBS itself as a result of its "thinking" process.
- The Knowledge Base (KB): The KB contains all of the knowledge/rules that are needed to investigate the construction described by the CM.
- The Man/Machine Interface (MMI): A KBS has a practical value only if it provides an efficient and easy to use MMI. The particular type of interface should relate to the type of information that is modelled by the CM. For example, KBSs that operate within the domain of Computer-Aided Design (CADn) require graphical interfaces, whereas others, such as fault diagnostic systems, need only textural information.

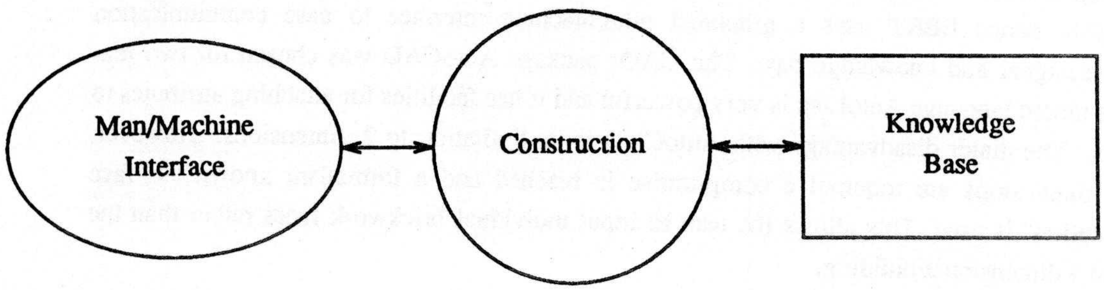

Figure 1 A typical knowledge-based system

The remainder of this section will contain descriptions of two knowledge-based systems that use the above architecture. The first of these is a system called BERT which stands for Brickwork ExpeRT and the second in known as GERT (Gypsum ExpeRT).

1. BERT - The Brickwork Expert

Background

Ibstock Products Ltd, a leading brick manufacturer, considered CAD for dealing with the generation of special shape brick components. Essentially, the technological problems that relate to the design of these components are material characteristics (there are over 80 different types of brick available), manufacturing implications and structural and performance criteria.

Part of the current research project is to address the problem of building a knowledge-based design system for evaluating brickwork proposals. The motivation for developing BERT was to investigate how far a knowledge base and a computer-aided draughting (CADr) system could be integrated on a PC. The knowledge domain chosen was brickwork cladding and initial implementations of BERT focused on the problems of movement joints.

BERT is implemented as a design advice system. Designers describe their construction and then BERT comments on this proposed design, pointing out problems and suggesting remedies. The designer then incorporates these suggestions into his design and resubmit this to BERT. The whole process is repeated until either BERT accepts the design as being the best solution or the designer decides to ignore BERT's advice on the grounds that it is too pedantic.

BERT uses AutoCAD for its graphical man/machine interface, a multi-formalism programming language (MUFL) for the knowledge-base and a Prolog type relational description for the construction model.

The input and output

Knowledge about movement joints within brickwork cladding requires a large amount of spatial information, hence BERT uses a graphical man/machine interface to ease communication between designer and knowledge base. The CADr package AutoCAD was chosen for two reasons: its macro language AutoLisp is very powerful and it has facilities for attaching attributes to drawings. The major disadvantage with AutoCAD is its limitation to 2 dimensions. However, when 3 dimensions are required a compromise is reached and a formalism known as "face representation" is used. This allows the user to input individual brickwork faces rather than the complete 3 dimensional building.

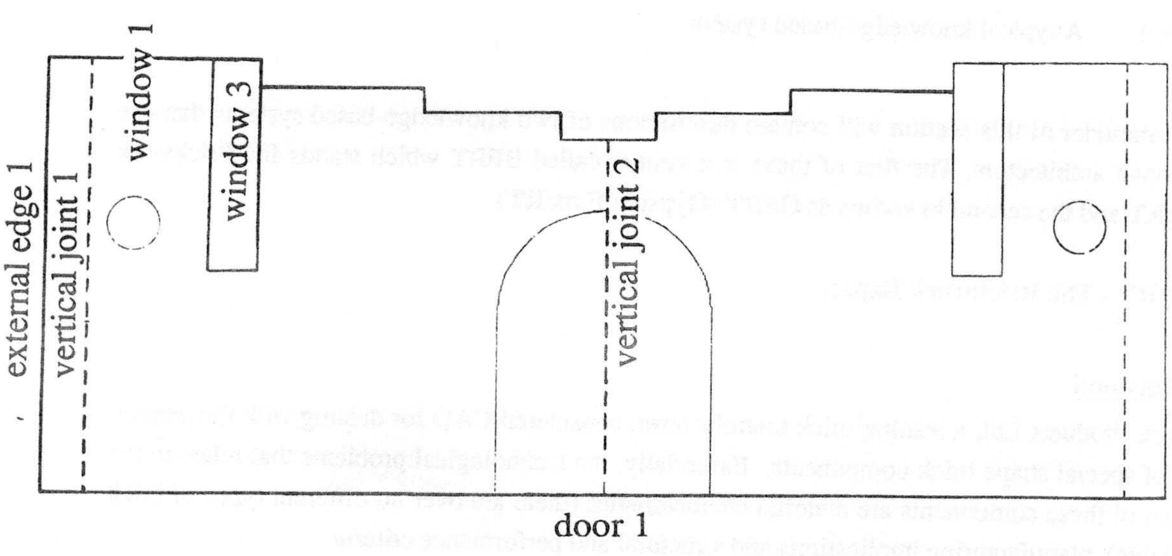

Figure 2 A building elevation using the face representation model

Examination of the knowledge domain indicates that there are a finite number of building elements which can affect the layout of movement joints. These include brickwork edges, openings, down-pipes, other movement joints and parapets. The user constructs a brickwork face by selecting a building element from a menu and then locates the element within the design. Each brickwork face representation (see Figure 2) provides the following information:

- the outline geometry of the face
- the position, shape, size and classification of each element in the face

Finally, by relating the individual faces to one another the knowledge base can "understand" the whole construction.

The current version of BERT only uses graphics for input, output is produced in a textural form (see figure 3).

Face: 6
Name: vertical-joint-1
Position: 1000mm right of external-edge-1

Comment:
12625mm left of vertical-joint-2
The gap of 12625mm between vertical-joint-1 and vertical-joint-2 exceeds the maximum permitted separation (12000 mms).
A vertical joint is required within this area. However, if a brick type with a smaller coefficient of expansion were selected, this problem would not arise.

Suggestion:
New Position: 3150mm right of external-edge-1
Reason:
This location is at the middle of a pier. Placing a movement joint at such a position is usually aesthetically pleasing.
Reason:
No further joints are required to protect the adjacent areas of brickwork.

Figure 3 An example of a consultation with BERT

The knowledge base

BERT's knowledge base is written in a language call MUFL (MUlti-Formalism Language) (Bowen 1985). This language provides both forward and backward chaining, procedural and declarative formalisms as well as mechanisms for functional programming and blackboard architectures. The deamon form of the procedural knowledge formalism was found to be the driving force behind the brickwork domain expert's knowledge and so this was used as BERT's overall control mechanism. Hence, BERT may be regarded as a forward-chaining expert system.

BERT's movement joint knowledge base comprises three main groups of deamons.

Group 1: provides general remarks on the movement joint layout proposal.

Group 2: remarks upon the location of individual movement joints.

Group 3: suggests possible improvements to a joint's location.

Other rules, such as those for printing results, are not considered as part of the actual movement joint knowledge.

The construction model

There are three types of information stored in BERT's construction model. The first of these is concerned with the spatial location of physical objects. Each building element that forms the construction has a physical description. For example, vertical joint 2 shown in figure 2 has a description of the form:

joint(Location, vertical-joint, vertical-joint-2).

The second type of CM information is similar to the first except that it describes conceptual objects. In this instance, a conceptual object is defined as an object that exists at a level of abstraction above the purely physical realm. For example, the mid-point of a pier is a conceptual object because it is an abstract concept whose existence relies on the presence of other physical objects, in this case windows. In figure 2 there is a mid-point of a pier between window 1 and window 3, this is described in the CM as:

mid-point-of-pier(Location, between window-1 and window-3, pier-1).

Finally, the CM contains information about the non-spatial properties of the construction. For example, figure 2 is built from the brick type Ibstock Golden-Multi Stock. This is represented as:

brick-type(face-name(face-1), 'Ibstock Golden-Multi Stock').

2. GERT - The metal-stud partitioning expert

Background

British Gypsum Ltd, (manufacturers of plasterboard products and suppliers of metal stud partitioning) is considering the use of computers to help respond to customer requirements for "standard" and "special" performance criteria from their products. These criteria include fire resistance, sound insulation, structural stability, minimum thickness and maximum height. In the case of metal stud partitions, a wide range of values for the criteria can be obtained by altering the design specification with regards to the number, types and location of components. For example, the number of partition boards used affects the overall structural stability, fire resistance, thickness and height. Each design specification - combination of components - has material cost and construction time implications.

The project is currently in the feasibility stage, although a prototype system called GERT has been implemented. GERT has two main functions: it is a component selection system and an automated component designer.

The input and output

GERT responds to two type of input. Firstly, the user can provide a partition specification in the form of values for the five characteristics of partitioning systems; height, thickness, weight, fire resistance and sound insulation. For example:

User Specification:

* Maximum Thickness -	200 mm	* Height -	9600 mm
* Weight -	unknown	* Fire Resistance -	1 hour
* Sound Insulation -	52 dB		

The second type of input is in the form of answer to questions possed by GERT. These questions relate to environmental factors that may influence the choice of partition system. For example:

Does the partition have a ceramic tile covering ? ---- yes

To what height do the ceramic tiles come ? ---- 3000 mm

Will the partition be subject to moisture ? ---- yes

Output from GERT is in both a textural and a graphical form. Text is used to describe the properties of the partition, whilst a graphical description shows the structure. For example:

Partition Characteristics

* Maximum Thickness -	78 mm	* Height -	4000 mm
* Weight -	28 kg/sq m	* Fire Resistance -	1 hour
* Sound Insulation -	46 dB		

Selected Design:

1 layer of 15mm Fireline board each side of 0.9mm gauge 48mm I studs, at centres of 400mm with 25mm minimum glass fibre mat.

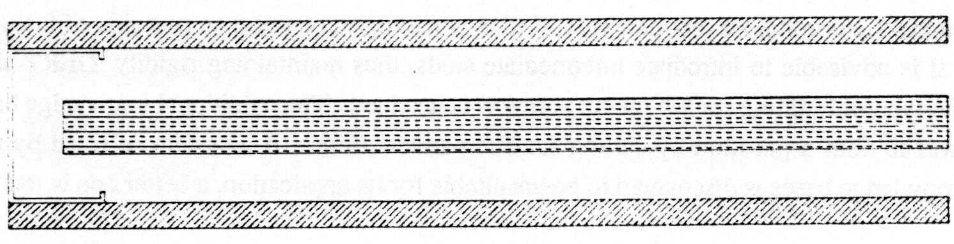

Figure 4 An example of a design specification produced by GERT

Figure 4 shows GERT's output for a specification that does not match any of the partition systems known to the British Gympsum catalogue. However, it must be stressed that this is an example and has not been validated by British Gypsum, neither has the knowledge used to generate it.

The knowledge base

GERT's knowledge-base can be regarded as three knowledge-bases in one; a partition selection system, a partition design system and an additional advice system.

Component selection: GERT has access to a catalogue of all British Gypsum's standard metal stud partition systems. Each partition system is described according to a number of elementary parameters. These include the number of partition boards, the type of board, the metal stud size, cross section and gauge and whether the system has a cavity fill. Each partition system also has a set of characteristics, such as thickness, height, weight, fire resistance (in hours) and sound insulation (in dBs).

GERT processes a user's request by finding all of the partition systems in the catalogue that match the user's specification. From all of the possible partition systems GERT selects the 'cheapest'. Most of the component selection task is purely data-base retrieval, however, the factors that govern cheapness are expressed in a rule based form. Thus, GERT can be said to exhibit intelligent data-base retrieval.

Component design: If the British Gypsum metal stud catalogue does not contain a partition system that matches the user's specification, GERT proceeds into component design mode.

Knowledge about each of the subcomponents of metal stud partitions is used to generate new designs. This knowledge includes, for example, the rule:

> *the use of two partition boards, instead of one, increases the maximum system height by 1200mm, increases the sound insulation by 12dB and doubles the fire resistance.*

Once again, if a number of suitable partition systems are generated then they are compared and the cheapest is selected.

Additional advice: An additional knowledge base has been incorporated to augment the choice of a suitable partition system. This knowledge base reasons about how the partition selected will perform within its environment. For example, if tiles are going to be hung on one side of the partition, then it is advisable to introduce intermediate studs, thus maintaining rigidity. GERT also considers the type of building for which the partition is destined. This additional knowledge base has the power to veto a partition by calling for alternatives. Hence, if a system selected by the other two knowledge bases is discovered to be unsuitable for its application, a better one is found.

The construction model

The CM used by GERT is small. It contains information relating to the partition characteristics, the number and type of components that make up the partition assembly and the addition environmental factors. The current version of the Cm does not store any spatial information, this must be generated by the KB as required.

A MULTIPLE KNOWLEDGE-BASE APPROACH

Ultimately, the construction industry is looking for knowledge-based design systems that aid the design of whole buildings (Wix, 1986) and not just individual elements, as in the case of BERT and GERT. Such systems will allow designers to manipulate the spatial arrangement of their buildings, while maintaining compliance with the rules of component assembly and other aspects such as energy targets. Detail design could be automatically verified, thus production requirements would become more immediately understood (Atkin, 1987). The benefits of this are that all the "technological" factors would be taken into account at the same time, thus avoiding the need for later changes to suit component details. For example, during the conceptual stages of building design the proposed form could be automatically assessed for compliance with brickwork cladding rules. If the form was deemed unfavourable, then appropriate actions could be taken at a far earlier stage in the design than at present.

Few attempts have been made to integrate knowledge bases towards producing a multiple knowledge-base system. We feel that one of the key factor that is hampering this area of research is concerned with the architecture of such a system and in particular, the role and design of the construction model.

Problems with existing Knowledge-Based Design Systems

So far, knowledge-based design systems have been developed using the simple tripartite model described earlier (see figure 1). Each knowledge-based design system comprises a single knowledge base, a construction model and a man/machine interface. The work on the BERT and GERT projects has demonstrated that although it is perfectly feasible to develop individual KBSs for different building component assemblies, the next stage of developing a multiple knowledge-base system requires a different approach. This is essential due to the following two factors:

1. Developing multiple knowledge-base systems

Few knowledge-based design systems can interact with one another. Knowledge-based design for whole buildings would involve the interaction of a large number of different knowledge bases, each of these representing different domains of knowledge. To facilitate this form of interaction, there needs to be a construction model of the proposed building design from which each knowledge base can obtain information. This CM needs to be general enough to encompass all the possible aspects of the proposed building design, yet detailed enough to provide a complete description with respect to each. The problem with existing knowledge-based design systems is that each one is based upon its own highly specialised construction model, and this contains only that information relating directly to the knowledge base. None of these models are general enough to be used as the basis for a knowledge-based design system for complete buildings.

One possible solution to creating a multiple knowledge-base system is to integrate existing KBSs by providing interfaces between each at the KB and CM levels (see figure 5). The problems with this solution are as follows:

- Separate interfaces are required between each communicating KBS. Since the number of KBS needed is theoretically infinite (and in practice very large), the number of interfaces required is the factorial of this.
- The CM is not a single entity, but rather the union of all the individual knowledge-based systems' CMs. Any particular part of the construction may be repreatedly defined by many of the separate CM. Therefore, to update any one of these definitions implies that all the other are invalid and require updates.
- To alter an individual KB within the multiple knowledge-base system could result in the need for extensive updates to all of the interfaces attached to that KB.

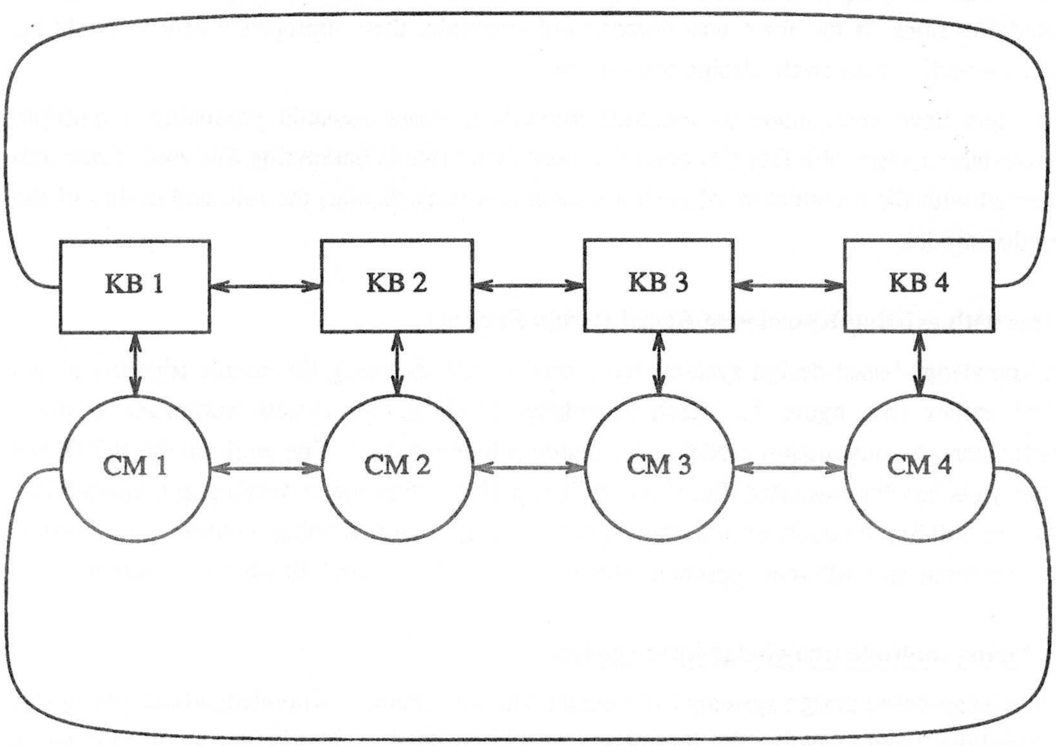

Figure 5 A multiple knowledge-base system based upon existing KBS

2. A generic construction model

A large factor included in the development time for knowledge-based design systems, is related to the implementation of the construction model. In the case of BERT, this was found to involve approximately one third to one half of the project. Since a generic CM does not exist, each development project must, presumably, consist of a similar amount of time. The solution to this problem is to design a generic CM that can be used as the basis for all future knowledge-based design systems.

The Coordinated Construction Model

The two factors given above clearly indicate the need for a rethink with regards to the architecture of the multiple knowledge-base system and in particular the emphasis for a new form of construction model.

An alternative architecture for the multiple knowledge-base system to that presented above is one in which there is only a single construction model (figure 6). This CM is central to all of the KBs and helps to coordinate them; hence the name 'Coordinated Construction Model' (CCM). Such a model will remove many of the factors that are seen as problem relating to the first system. For example:

- each KB will require only one interface to the CCM. The CCM would act as both the model of the construction and a blackboard upon which KBs will communicate.
- the CCM is a single central entity, thus component definition occur only once.
- updating an individual KB only affect the single interface between this KB and the CCM.

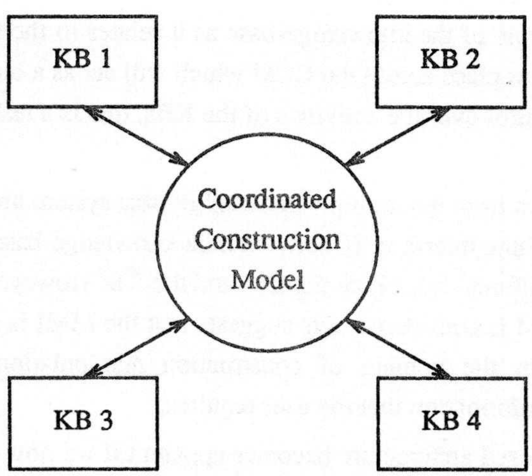

Figure 6 A multiple knowledge-base system based upon a CCM

Examining the requirements imposed upon the CCM reveal two distinct characteristics. Firstly, the CCM must represent every aspect of a construction, from the nuts and bolts to bricks and mortar. We shall regard this property as the core level of the CCM. The second characteristic of the CCM is the ability to provide information relevant to the whole range of possible KBs, this we shall call the interface level.

Core level

The core level of the CCM relates to the complete building design proposal and is a representation of the fundamental model known to the designer. It will be implemented as a data-base system. Each component used to form the construction will have an entry in the core level. These entries will represent such information as, for example, spatial location, relationship to other objects, size, substance and texture. The core level will also be needed a mechanism for relating levels of abstraction, for example, a wall can be an abstraction from an area of brickwork, which in turn is an abstraction of a set of relate bricks and mortar. Finally, a mechanism for assigning default values and inheritance is required. For example, even if the substance of a wall is unknown it still may have acoustic properties and these can be set by a default value or inherited from some other part of the construction.

Interface level

It is the job of the interface level to provide view of the core level that relate to the additional building models (mathematical models, geometrical models, structural models etc.) that are used by the specialist knowledge bases. These are generated directly from the core level, as and when they are required.

Knowledge bases

Finally, we shall consider the role of the knowledge-base as it relates to the CCM. Communications between separate KBs takes place across the CCM which will act as a blackboard. However, the CCM will not have any control over the activities of the KBs, this is a task concerning higher level knowledge bases.

An interesting point that follows from the multiple knowledge-base system architecture proposed, is the function of the man/machine interface. In conventional knowledge-based system, the MMI has performed a unique role, different from both the CM and the KB. However, if the relationship between the MMI and the CCM is considered, this suggests that the MMI is merely another type of KB; one that functions in the domain of construction manipulation, having specialist knowledge about the types of information that the user requires.

Another advantage of the proposed architecture becomes apparent if we now consider CADr systems as MMIs. One of the major problem with existing CADr systems is their inability to exchange data. This problem would be automatically overcome using the proposed architecture, since the interface protocol between KB and CCM could be used as the data exchange protocol between two CADr systems.

A major drawback with a multiple knowledge-base system developed upon a CCM is due to the uniform representation requirement of the CCM. Such a representation is highly unlikely to match any existing CM and definitely could not match them all. Hence, it will be difficult to incorporate existing knowledge bases into this system. Figure 7 might suggest a possible solution, whereby, existing KBs maintain their own CM which are in-turn linked to the CCM. If this is adopted and all KBs developed in the future use the CCM representation, then a gradual progression toward the ultimate system will occur.

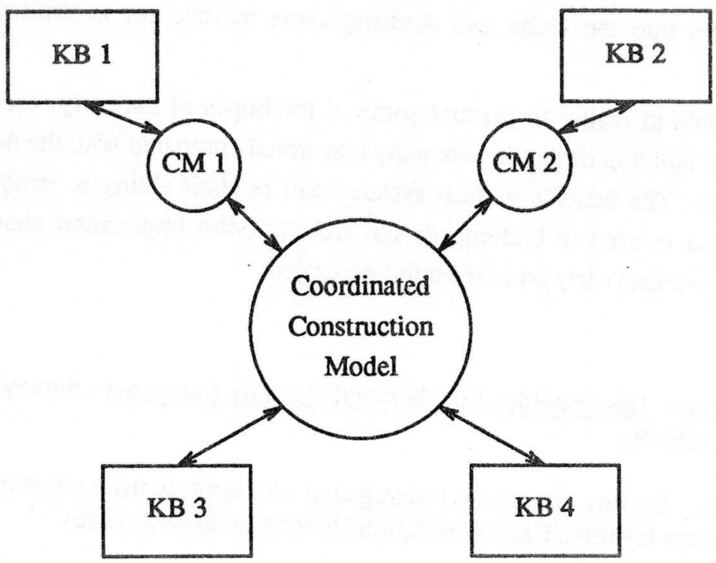

Figure 7 A multiple knowledge-base system incorporating existing KBS and a CCM

CONCLUSION

The implications of this approach to developing a multiple knowledge-base system for whole building design are two-fold. First, it raises the question of the usefulness of existing CADr systems that are currently being used in building design practice. As the basis of a coordinated construction model they are limited because they essentially have only a geometrical view of the building and the CCM must serve both as a geometric and functional model. There are also many different CADr system in use, which poses the subsequent problems of data exchange. Some initiatives have been launched to overcome the problems of geometric and non-geometric data exchange; namely PDES and its predecessor IGES (Wix and McLelland 1986). It is too early to judge whether such protocols can be used as the basis for the CCM. However, if they are, then is it envisaged that CADr will become one of the input/output devices of the multiple knowledge-base system.

The second implication is how the short-term and long-term objectives can be reconciled in what will certainly be a major research project. In the short term it will be necessary to develop a variety of knowledge-based system to understand the complexity of the CCM and to gain industrial support by demonstrating their practicalities. Both of objectives are equally important in order to achieve the long term goal; the creation of a multiple knowledge-base system to aid whole building design. However, the approach suggested in this paper should conveniently allow this to happen as the individual KBs within the multiple knowledge-base system are independent of the CCM so long as they communicate with their own construction model using the same protocol as the CCM. Integration of related KBs (e.g. coordination of brickwork elements, window components and steal-framed structures) into the multiple knowledge-base system will be a matter of plugging the KBs into the CCM and devising some method for controlling their activity.

Finally, it now seems feasible to realise in practice some of the hopes of the early researchers. Although, the task of whole building design is extremely non-trivial compared with the design of individual building elements. The benefits in such systems will be their ability to structure the ill-structured knowledge that is used in building design and that vital implication about component interactions will be evaluate early on in the building project.

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