An integrated approach to CAD: modelling concepts in building design and construction

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The ICON project is concerned with the creation of a generic information structure for the construction industry. A central feature of the information model is the use of object-oriented modelling techniques to allow information to be viewed from different 'perspectives' and at different levels of abstraction, according to the requirements of the user. This paper discusses the object modelling of concepts and information in the design area. Drawing on knowledge elicited from protocol analysis of the design activity, a series of interrelated object models has been developed, reflecting different perspectives and abstraction levels within the design domain. Three of these models (spatial design, physical design and structural design) are presented and their implications for the communication and sharing of information discussed.

Keywords: information/integration, object modelling, design models, perspectives, knowledge elicitation

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Whatever else it may entail, the design process ultimately generates new information, much of which will have to be interpreted, mediated and acted upon by others. In a building project the route from design to construction can be very involved. It characteristically brings into play many different actors from different disciplines, all with their own working methods. In the absence of an established integrating framework, communication between the various parties is often poor and the necessarily large amounts of complex information are neither managed efficiently nor co-ordinated effectively.

Within architectural practice Computer-Aided Design packages are now increasingly widely used. Though still for the most part a drafting tool rather than a true design aid, CAD does provide the designer with a reliable and consistent method of presentation. Providing agreement is reached on coding conventions, CAD can therefore be used as a basis for data sharing among members of the design team, obviating the need for hardcopy: exchange of discs replaces exchange of drawings[1]. Useful as it may be, this approach is still limited. Communication with others involved in the construction process, trade contractors, subcontractors, project and facilities managers, will not be much enhanced by the use of such tools unless they are tied into an overall information framework.

The ICON (Information/Integration for CONstruction) project, to which the present paper relates, addresses this need for a strategic framework. The aim has been to establish the information requirements of the various disciplines involved in a construction project and to develop a structure into which all models can fit, irrespective of their level of abstraction. The design model discussed below is the outcome of a specific study undertaken within the context of this larger information framework.

1 Background: recent developments

Over the last few years the issue of integration has become increasingly prominent, forming the theme of a number of recent seminars and workshops[2,3]. The growth of research in this area parallels various efforts at establishing international data standards, and reflects a concern over the rather piecemeal and *ad hoc* way in which computer technology is being applied in the different domains. CAD systems, word-processing and database packages are now familar parts of the scene, but are generally adopted as stand-alone applications and the links between them are poor or nonexistent. This can lead to much redundancy and wasted time, as information is successively transcribed and entered into new data systems. It is also a major barrier to information co-ordination.

1 Cross reference *Building* (8th May, 1992) pp 52–53
2 *Computer Building Representation for Integration* Second International Workshop, Aix-les-Bains, France, 3–5 June 1991
3 *The Computer-Integrated Future* CIB Seminar, Eindhoven University of Technology, Calibre, The Netherlands, 16–17 September 1991

Amongst the growing literature on information modelling within the construction industry, various methods have been proposed for integrating building design and construction[4–6]. Much of this work, however, still centres on stand-alone applications. While a larger information framework may be alluded to, within which different applications may fit, there is as yet no clear strategy as to how such a framework is to be built or how it will operate.

Most information modelling within the construction industry has tended to follow one of three main approaches: data modelling, process modelling, or product modelling.

1.1 Data modelling

Data models set out to identify and define items that are of interest to the construction industry. These have come to the fore through a large international standards effort, STEP (STandard for the Exchange of Product model data), which will eventually allow information to be translated between various CAD/CAM systems. Whilst the original concern of STEP was product modelling (see below), its areas of application are actually much broader than this. The main tools used are graphical schema languages, such as ERD, NIAM, and IDEF1X, and data definition languages, such as EXPRESS. An entity relationship diagram (ERD) models the world in terms of entities, facts about them (attributes) and relationships between them. (NIAM) Nijssen Information Analysis Modelling is a data modelling technique that does not distinguish between entities and attributes. IDEF1X is an enhanced entity relational modelling technique. NIAM and IDEF1X are both used in STEP. The data definition language, EXPRESS, adds a number of concepts, such as rules and methods, that cannot be modelled in standard graphical tools. For a detailed discussion and evaluation of the various graphical information models, the reader is referred to Fereshetian and Eastman[7].

1.2 Activity modelling

This involves the modelling of activities in a project and the data and material flows between them. Activity modelling helps to provide a simplified picture of the construction process. Among work to date, Sanvido[8] has developed an integrated process model that shows the hierarchical structure of functions and sub functions performed in a construction project. Midken[9] has also tried to identify the different functions within the construction industry. IDEFO is a widely used activity modelling technique, and SADT (Structured Analysis and Design Technique) uses data flow diagrams in addition to entity relationship

4 Sanvido, V 'A top-down approach to integrating the building process' *Eng with Comput* Vol 5 (1991) 91–103

5 Howard, H C 'Linking design data with knowledge-based construction systems' *CIFE Spring Symposium* (1991) pp 1–24

6 Fenves, S J, Flemming, U, Hendrickson, C, Maher, M L and Schmitt, G 'Integrated software environment for building design and construction' *Computer-Aided Design* Vol 22 (1990) 27–36

7 Fereshetian, N and Eastman, C 'A comparison of information models for product design' *The Computer-Integrated Future* (1991)

8 Sanvido, V 'Linking levels of abstraction of a building design' *Building Environ*, Vol 27 No 2 (1993) 195–208

9 Midken Final Report for CISC The Business Development Centre, Midken Ltd, London (1991) models for data modelling. Some work has also been done using object-oriented methods to integrate activities with product models[10].

1.3 Product modelling

Much of the prototype work in this area has been done by VTT (Finland)[11,12]. Product modelling focuses on the components found in a building and the relationships between them. In providing a conceptual description of a product, this kind of model aims to structure all the information necessary for the design, manufacture and use of that product. In practice, however, product models do not have the ability to address the differing information requirements of the various disciplines involved in the construction industry at a detailed level.

Perhaps as a response to these difficulties, recent research in the field of product modelling[13] has tended to concentrate on the building of localized models rather than global solutions. In his latest work it appears that Björk has moved away from product modelling towards an approach similar to that used in the present project.

From the point of view of strategic modelling, all of these current approaches have the weakness that they imply a separation between the data and the processes performed on the data. In order to avoid having to compromise to reconcile the differing information requirements of different users of the information, it was considered important in this project to combine the data and the process at all levels. This facilitates the representation of abstract concepts, as used by workers in the various disciplines, and the relationships between them. The design model illustrates this approach, but also throws into relief specific issues and problems.

2 The design process

There is much about design that sets it apart from the rest of the construction process. Compared, for example, with construction planning, the process of design is difficult to describe and remains poorly understood. While it is indisputable that design forms a bridge between human needs and physical reality[14], it has long been recognized that physical form can never be generated simply by a process of logic and deduction, using only a set of design criteria and nothing else[15,16]. Some formal idea, however rudimentary, must always be present, and a design 'solution' characteristically arises through a complex, iterative process, in which ideas are developed, modified, or abandoned in the light of site constraints, programmatic requirements, and a whole host of other factors, as well as the 'internal' demands of the architectural language

[10] **Hendrickson, C, Zozaya Corstiza C, Rehak, D, Bavacco-Miller, E and Limp, P** 'Expert systems for construction planning' *J. Comput. Civ. Eng, ASCE* Vol 1 No 4 (1987) 253–269

[11] **Björk, B-C** 'Basic structure of a proposed building product model' *Computer-Aided Design* Vol 21 No 2 (1989) 71–78

[12] **Björk, B-C and Pentilla, H** 'Building product modelling – experiences of prototype development' *Microcomput. in Civ. Engng* Vol 6 (1991) 267–279

[13] **Björk, B-C** 'A conceptual model of spaces, space boundaries, and enclosing structures' *Automation in Construction* Vol 1 (1992) 193–214

[14] **Gero, J S** 'Design prototypes: a knowledge representation schema for design' *A.I. Mag.* Vol 11 No 4 26–36

[15] **Alexander, C** *Notes on the synthesis of form* Harvard University Press, Cambridge, MA (1964) pp 7–8

[16] **O Catháin, C S** Is design logically impossible? *Design Studies* Vol 3 No 3 (1982) 123–125

itself. One of the most familiar and long-standing maps of the design process, the 'analysis-synthesis-evaluation' model[17], suggests a way of dividing design into distinct activities, albeit at a high level of abstraction. But even this proves wanting. This compartmentalization of the design process has been emphatically refuted by more recent research[18,19], which reaffirms the complex and interactive nature of 'real-life' design. According to Akin, design behaviour is marked out by the constant generation of new task goals and redefinition of task constraints.

From the point of view of information modelling, therefore, the design phase presents a distinctive problem in that its elements are so highly interdependent. Designing is, in effect, all of a piece. To some extent these difficulties apply beyond what might normally be thought of as design in the narrow sense. Thus the writing of the brief or programme, which might be regarded as a fairly discrete activity, is in fact closely intertwined with the business of designing. Not only is it impossible, in principle, to establish *ab initio* a complete and comprehensive list of design requirements for any project. It is also far more practical, in many cases, to develop a brief interactively through comment on, and criticism of, an actual design proposal[20]. The definition of requirements and the evolution of the design go hand in hand.

A sharper division can be said to exist between architectural design and other, related areas such as structural design, electrical and mechanical engineering etc. This is because these other aspects of design all involve special expertise and are normally carried out by different members of the project team. Structural engineers, electrical engineers, and others also bring different perspectives to bear on the design 'problem', according to their particular emphasis and professional orientation. The notion of different 'perspectives' is central to our information model and will be discussed in detail below.

It is worth noting, however, that even here the degree of separation is not fixed and immutable: it depends very much on the standpoint of the design team and the working methods they choose to adopt. In the post-War period the grid layout became widespread as a way of systematizing planning. It was used to achieve efficient use of space and economical use of materials. Grid dimensions may be prescribed by the form of construction, as, for example, in the case of prefabricated building systems for schools. Alternatively, these would be arrived at by weighing functional considerations, the desirable size of offices, the space required for typical furniture and fittings, against structural demands, the economic span of beams, the bearing capacity of walls and floors etc.

[17] **Jones, J C** 'A method of systematic design' **N Cross** (ed) *Developments in design methodology*, John Wiley, Chichester, UK (1984) pp 9–31

[18] **Akin, O** 'An exploration of the design process' **N Cross** (ed) *op. cit.*, pp 189–207

[19] **Akin, O** *Psychology of architectural design* Pion Ltd, London (1986)

[20] **Lawson, B** *How designers think: the design process demystified* Butterworth Architecture, Guildford, UK (repr 1991) pp 35, 88

Leaving aside the wider implications of grid-planning as an architectural device, one of its effects was that it produced a 'decoupling' of information systems, allowing the architect and the structural engineer to work more independently than would otherwise have been the case. The architect could now concentrate on internal planning, the structural engineer could work out the column spacings, and minimal interaction was required between them as long as they adhered to the discipline that had been imposed. The unlinking of systems in this way clearly has certain advantages in terms of information handling. It also has disadvantages, one of the main ones being that it acts as an obstacle to innovation.

A similar decoupling can be observed to have taken place between architectural design and lighting design, once daylighting from windows became subordinated to artificial lighting, as occurred in this country from the early 1960s. As the window lost its importance as a light source, the architect could design the building envelope as a more or less self-contained exercise. Only the amenity value of the window (the view out) need be considered. The lighting engineer could then independently design the layout of fittings necessary to achieve the increasingly high levels of illumination that were required across the whole of the working plane. This separation of architectural from lighting design was also facilitated by the adoption of a modular system of planning: a secondary grid would normally be employed with fittings placed at regular intervals. The emphasis on uniform ambient lighting was at the same time underpinned by a growing pre-occupation with internal flexibility (the open plan) and by a concentration in lighting studies on threshold visual acuity at the expense of visual quality.

Amongst the present generation of architects, few now look favourably upon these developments. The grid is condemned as much for the bland and repetitive environments it generated as for the dysfunctions that often resulted. (For a swingeing attack on the mechanistic approach that became associated with grid planning and prefabrication, see Kroll[21]. Many contemporary architects are concerned, in their different ways, once again to develop an architecture that responds to the specificities of programme and context[22]. From the viewpoint of the present project, however, the important point is that once the designer abandons such generalized and normative methods, the need for close communication and interaction accordingly increases. The more peculiar, the more specific the solution, the more closely interwoven is the work of the design team, and hence the greater the need for an effective framework for the exchange of information.

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[21] **Kroll, L** *The architecture of complexity* (trans P Blundell Jones) Batsford, London (1986)

[22] **Mayne, T** 'Connected isolation', **P Noeven** (ed) *Between deconstruction and new modernism* Austrian Museum of Applied Arts, Vienna (c. 1991)

3 The ICON model

Most conventional analysis and modelling techniques (see above) deal with the data and the process aspects of information quite independently. Data modelling is used to establish the different pieces of data that it is necessary to store to support the various processes involved; process or function modelling is used ultimately to determine how the data are to be manipulated. One of the fundamental premisses of the ICON project was that data and processes should be considered alongside each other, in order to clarify the interactions between them: to show which processes act on which data and what changes are made to those data. Also (above all) the aim was to allow abstraction away from computer-related concepts to more domain-oriented concepts. The approach adopted was a hybrid one, that combines the strengths of information engineering with those of newly developed object-oriented modelling techniques[23].

3.1 Information engineering

Information engineering is a methodology that was designed to simplify the development of information systems. Its chief application is in business, where it is used to assist in the alignment of information technology with industrial goals, objectives and critical success factors[24].

The information engineering method (IEM) is a top-down approach, applicable at the enterprise rather than the project level. This makes it especially useful for addressing high-level management and scoping issues. In ICON, IEM and its associated computer-aided software engineering (CASE) tool, the information engineering facility (IEF), were used to analyse and structure the activities that are carried out in a construction project, providing a framework for the later object-oriented modelling. The framework consists of a hierarchy of activities performed in building construction, of which design forms one part; this hierarchy is then decomposed into further hierarchies. Although a number of authors disagree with the use of activity decomposition as a starting point in object-oriented modelling[25,26], it was considered valuable in this project as a way of making sense of the complex and diverse activities involved in construction. Moreover, close study of the process allows the object classes relevant to that process to be identified.

3.2 Object modelling

In object-oriented analysis the world is modelled in terms of object types and their behaviour. Among the fundamental concepts underlying object orientation are *object types, classes* and *instances, operations, encapsulation, abstraction, inheritance* and *polymorphism.* These will be illustrated

23 **Sarshar, M, Powell, J et al** 'Object-oriented and information engineering: a hybrid approach' *Int. J. Const. Inf. Technol.* Vol 1 No 2 (1993) 83–96

24 **Martin, J** *Information Engineering* Vol 1–4, Savant, Lancashire, UK (1986)

25 **Foster, E, Barnard, A, Roberts, S and Wren, A** PoeT: object engineering in public transport *Object Technol'93* Cambridge (1993)

26 **Daniels, J** *Modelling with objects* Object Designers Ltd (1990) below with reference to specific design models produced in the project (for precise definitions see Martin and Odell[27]). The particular object-oriented CASE tool used in this project is process technology (PTech), produced by Associative Design Technology in the USA.

Object-oriented techniques have been used to enrich the ICON model and to overcome the deficiencies of IEM at lower levels of abstraction. One of the main shortcomings of information engineering, for our purposes, is its tendency to impose too rigid and inflexible a structure on activities and data. This was especially evident, and significant, with respect to design, where the modelling tool did not begin to do justice to the rich and complex processes discussed above. In addition, the fact that IEM manages complexity by dividing a model into subject areas makes it necessary to compromise when attempting to accommodate the differing information needs of the various parties, since each entity in the model may appear in only one subject area. To avoid such compromises, a series of object-oriented models was developed, allowing the individual perspectives of the different actors and disciplines to be incorporated within the one model.

4 Modelling perspectives

The concept of perspectives is a key one in the ICON model and requires clarification. Since the primary aim of ICON is to enhance the integration of information across different domains within the construction industry, the mechanisms by which objects are identified and linked together are clearly critical. In object orientation, an object consists not only of attributes, as in conventional entity relationship modelling, but also of the actions that may be performed by or on it. These actions, or *operations*, show the activities that can be performed but hide the physical implementation (method) of the action. This hiding of information is known as *encapsulation.* Often the same calculation cannot be used to perform an operation under all circumstances, so there may be many different methods underlying the operation. This is termed *polymorphism.*

Reference has already been made to the use of abstraction, which is of great importance in information modelling. Abstraction levels are built up in various ways, the two most important being *aggregation* and *generalization.* Aggregation is a mechanism for grouping together a number of objects referring to them as a single item. Thus the concept 'house' may be used to encapsulate a whole cluster of features, ranging from physical characteristics (a built object consisting of rooms, passages, stairs, walls, ceilings, floors etc.) to ideas such as ownership, occupancy, usage, functional requirements, legal rights and obligations. Generalization, on

[27] **Martin, J and Odell, J** *Object-oriented analysis and design* Prentice Hall, Englewood Cliffs, NJ (1992)

the other hand, allows information to be represented regarding a whole range of objects that are different in many respects, but are similar or identical with regard to a particular context. Used in this way, the generalization 'house' can be applied, where appropriate, in very different contexts, where the exact characteristics (the number of floors, the form of construction etc) are unimportant. Object-orientation supports the use of abstraction by mechanisms that represent both aggregation and generalization directly. These mechanisms are object *composition* and *inheritance*, respectively.

A key issue that arises when casting the information net across a congeries of different disciplines, is that each of these may wish to aggregate and classify concepts in a different way. Thus certain members of the design or construction team may view an object-type quite differently from others. They may also work at quite a different level of abstraction: one person's object is another person's class. All this makes for a very large and complex overall model. Such a model will probably be impossible to draw, let alone understand, as a whole. For practical purposes, however, it is neither necessary nor appropriate to grasp the model in its totality: the various users are concerned only with that section of the information model that reflects and serves their own needs. By focusing on the different 'perspectives' of the users, rather than on the whole model, ICON aims to achieve a more realistic representation of the information needs specific to each domain. This is a contrast to normal entity-relationship modelling methods, which require a lowest common demoninator to be reached among the various views of information.

The concept of information perspectives may be seen as directly analogous to the way in which a building design is normally represented on paper. In that case, different drawings are produced that represent the different 'perspectives': plans, sections and elevations convey the overall form and layout of the building, overlays are used to work out other aspects of the design, (structure, services, etc.) and particular kinds of drawing (schematics, production information) express the design at different levels of detail.

The method used in ICON has been to build a number of separate entity-relationship models, each representing a specific domain or viewpoint. The final object-model represents a synthesis of these different entity-relationship models. This does not mean that the models are treated in isolation. One of the distinctive features of this approach is that an entity may appear in more than one context, and hence, in more than one perspective model. It follows that one of the most important tasks facing the analyst is to establish when a particular concept is the same as that in another perspective or, alternatively, when it is a subtype or supertype of that concept, or even when it shares a common supertype with that concept.

Figure 1 illustrates the principle of perspectives. At the top are the three broad areas into which the field of building construction is decomposed: design, procurement and construction. It is important to note, however, that the perspectives are not a simple reflection of this initial tripartite division. The method allows different views within as well as between these domains, thus producing a series of models, which capture more of the richness and dynamism of the 'real life' situation. Furthermore, although most are low-level models, arrived at through progressive decomposition, this need not always be the case. As will be seen, high-level object models can be, and have been developed for perspectives at the top of the hierarchy, providing a high-level overview of the objects involved in processes.

5 *Eliciting design knowledge*

To begin with, the design model, like the rest of the ICON framework, was constructed from information documented in books and research papers and from interviews with academics and practising members of the professions. The results were then validated by a group of professionals, who were involved with the ICON project through all its stages. To further improve the information infrastructure that was developed, and to identify gaps within this, a systematic method of knowledge elicitation was employed within a workshop setting. The method used was a direct one, known as 'protocol analysis'.

Knowledge elicitation is essentially a process of locating, collecting and refining knowledge about a particular domain. In protocol analysis, this is achieved by encouraging an expert in the field to think aloud, and to describe what he or she is doing and why. This is a well-established approach to knowledge elicitation[28]. It has been applied to the field of architectural design by Akin and others at Carnegie-Mellon University[29]. In the ICON study, representatives were brought together from the domains of architecture, procurement, contracting, building and information technology in a two-day workshop. A series of sessions was organized, some multidisciplinary, others composed only of academics and practitioners from the same discipline. All sessions focused on a specific case study (the design of a church), enabling the workshop to follow the full life-cycle of a construction project from briefing and analysis through to project completion. The IT members of the groups did not participate

[28] **Garzy, J and Ibbs, W** *Knowledge elicitation: a practical handbook* Prentice Hall, Englewood Cliffs, NJ (1990)

[29] **Akin, O, Dave, B and Pithavadian, S** 'A paradigm for problem structuring in design' *Proceedings of the IFIP W.G.5.2. Workshop on Intelligent CAD*, Cambridge, MA (1987)

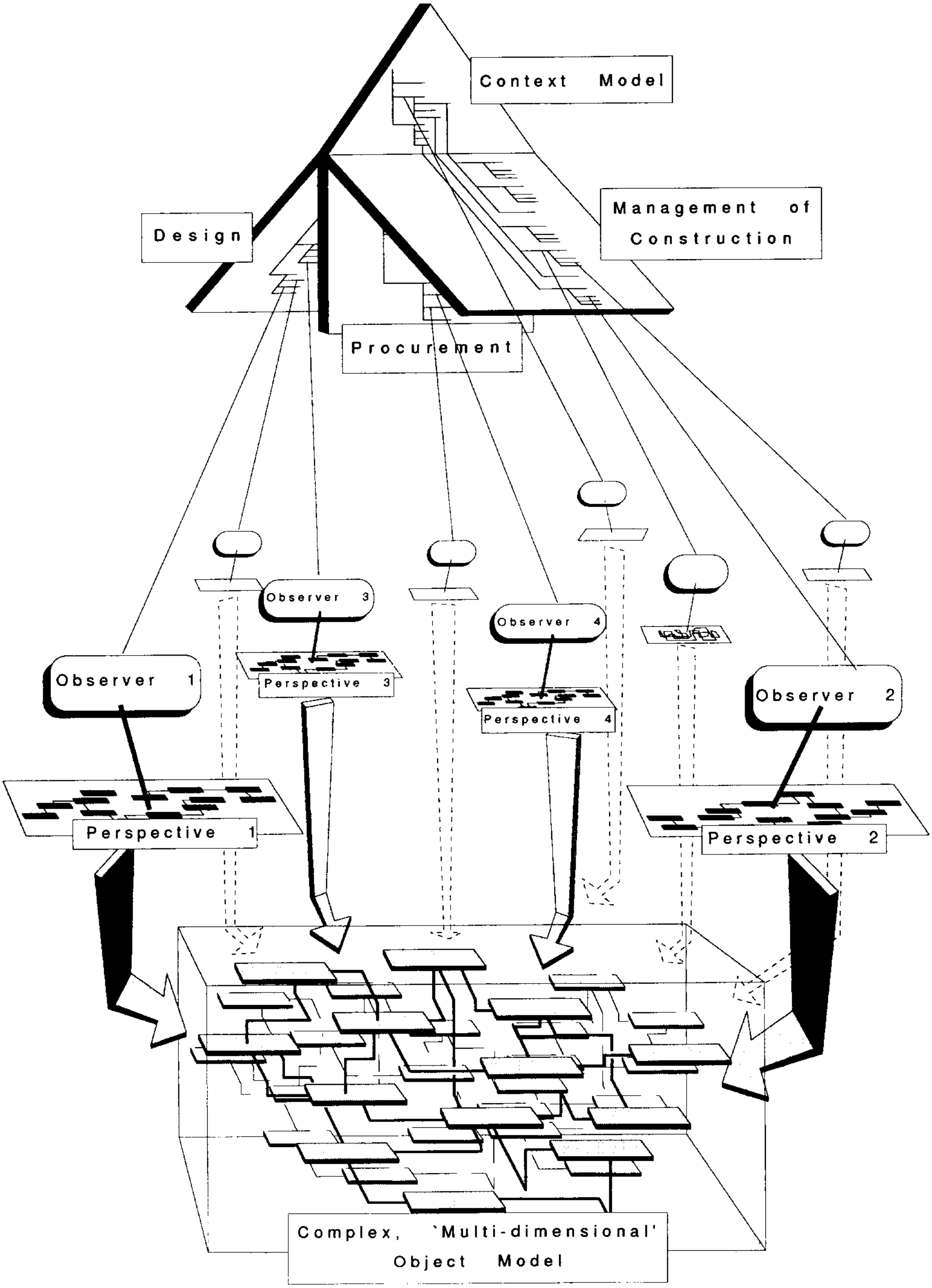

Figure 1 Individual perspectives within a single model

in the discussions, but acted as facilitators and rapporteurs, recording the information and knowledge that was extracted during each session[30].

Although there are many examples of knowledge elicitation from experts, this is normally done on an individual basis. The method used in this case was unusual in that it involved many different experts in different domains, and thus revealed the way they interact with each other. The sessions helped to highlight the areas of overlap between disciplines and the different perspectives that were brought to bear on these areas of common interest. Thus the concept of site was shared by all participants in the design and construction process but the data requirements varied widely owing to the different perceptions, and hence priorities, of each of the actors. While the architects were concerned principally with establishing the size, form, and location of the building and with the aesthetic potential of the site, those involved with procurement gave their attention to access, the level of the water table, and physical features that might involve civil engineering works, owing to the cost implications that these might have. For the contractors the critical issues were placement of site facilities, storage areas and vehicular access.

More significantly, for the present purposes, the various parts of the overall information model were modified in the light of the protocol analysis, but in different ways. In the case of the construction planning model, it was found necesssary to specify additional objects (e.g. the tender programme), that were missing in the original model. With respect to the design model, however, the analysis prompted, not further decomposition or addition of objects, but a move up to a greater level of abstraction. The conceptual design object model (Figure 2) is a very high-level model, that addresses the earliest phase of design, when ideas, requirements, and options are being juggled in one mental process. Many different possibilities may be considered and discarded at this stage, and the model reflects the informal and iterative nature of this activity. Note that as different options are generated in outline form this may lead to reformulation of the requirements.

6 *The design model*

Since it is unrealistic to describe design in terms of a process flow, a breakdown was used which divided the design activity into three broad areas: space (architectural design), structure (structural design) and services (technical design). Architectural design was further broken down into 'spatial design' and 'physical design'. Object models were developed for each of these areas (see Figures 3 and 4). All the design areas are closely intertwined and the models are not intended to correspond exactly

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[30] **Aouad, G F, Ford, S, Kirkham, J, Brandon, P S, Brown, F E, Child, T, Cooper, G S, Oxman, R E and Young, B** 'An approach to knowledge elicitation in the construction industry' *ICON Research Report* Information Technology Institute, University of Salford, Manchester, UK

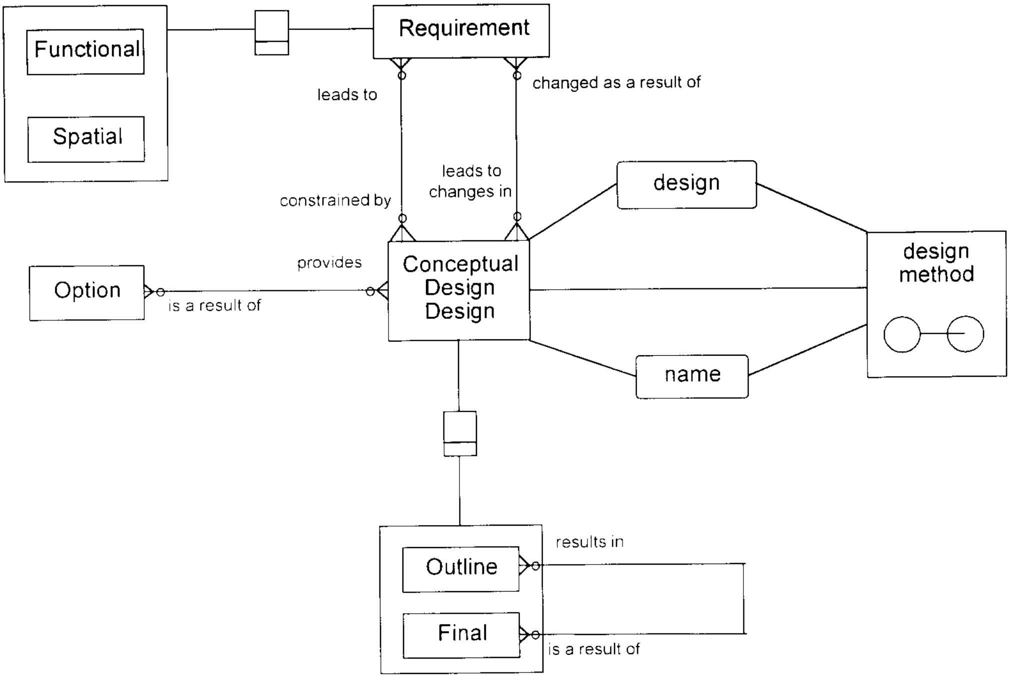

Figure 2 Conceptual design object model

to professional disciplines. The conception of buildings in terms of space and spatial relationships, however, is considered as central to the architectural perspective, and is in clear distinction to the emphasis on the physical elements of building and their performance (structural design), which is typically the realm of the structural engineer.

6.1 The spatial design object model (Figure 3)

At this stage space is still a fairly abstract notion, loosely defined in terms of functional use (and expressive quality), rather than viewed in precise geometrical and dimensional terms. Each space in the object model may form part of another space or be composed of other spaces. The relationship of the object class 'function' to 'spatial concept space' serves explicitly to recognize this, allowing the ground floor of an open-plan house, for example, to be considered as composed of secondary spaces, all fulfilling secondary requirements.

In addition each space may contain one or more spatial groupings or be part of one or more spatial groupings. There are many ways of grouping

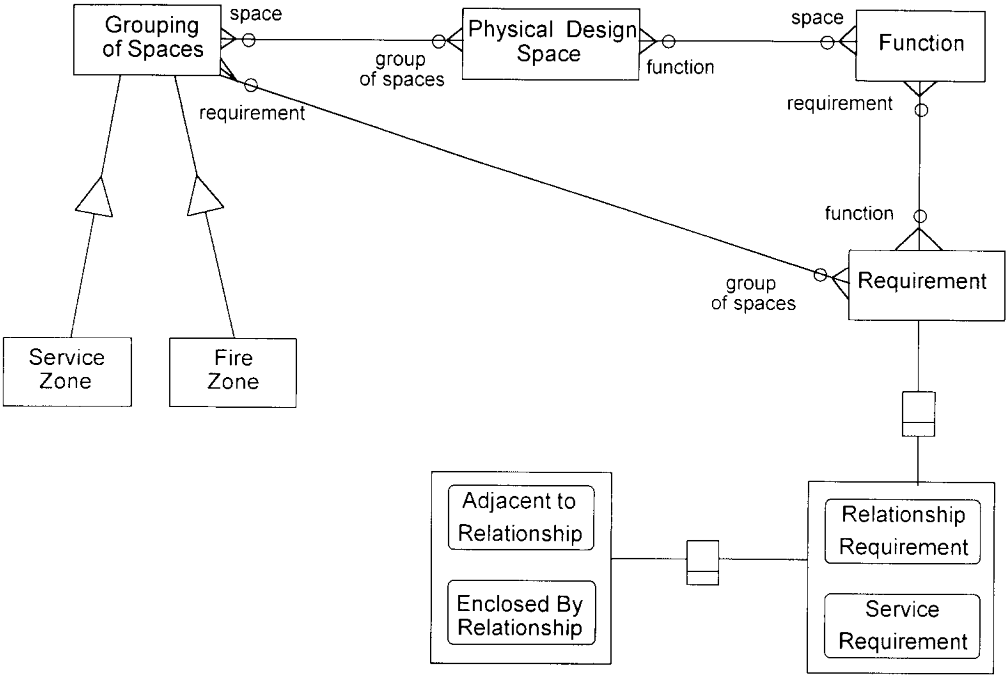

Figure 3 Spatial design object model

spaces, some of which are shown through the subtyping of the object class. The subtyping was undertaken using generalization rather than partitioning, since partitioning imposes mutual exclusivity. This is too rigid, since it is possible for overlaps in spatial groupings to occur. Grouping of spaces does not necessarily mean that spaces are physically adjacent: implied groupings also occur. Thus certain rooms within a building may need to be air conditioned, but these rooms are not necessarily situated next to one another although they do constitute a spatial grouping.

The notion of 'service zone' or 'service core' is well established in architecture, referring to elements of vertical circulation (stairs, lifts, lobbies, landings etc.) and associated areas of ancillary accommodation (toilets, utility rooms, kitchens etc.)[6]. Because of their special service requirements (plumbing, mechanical or electrical connections) it is often convenient in this case to locate these spaces close to one another in a particular part of the building. In multistorey office buildings it is common practice to cluster such 'support' facilities to ensure minimal interruption

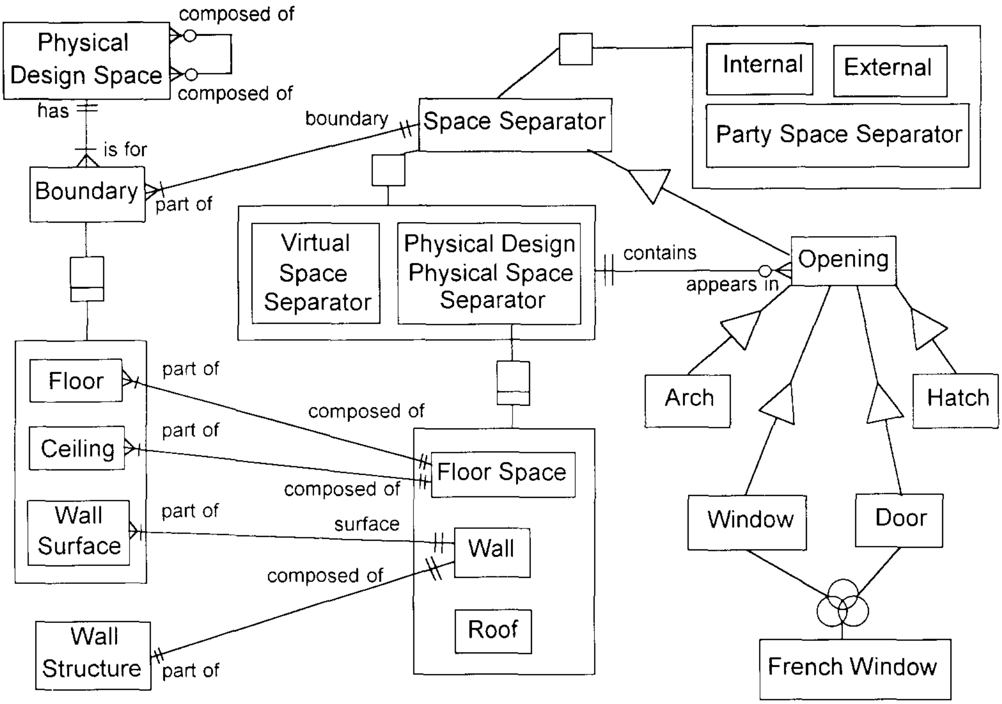

Figure 4 Physical design object model

of the rentable floor area[31]. This gives the grouping a certain physical reality. But it may still be useful to treat the service elements as a grouping within the model, even if they are physically distributed throughout the building.

Any individual space or grouping of spaces has certain requirements, e.g. in terms of servicing, as just described, or relationships, or both. 'Enclosed by' and 'ajacent to' are relationship requirements that may be specified for certain spaces (either bounded or functional). The 'adjacent to' relation also includes the requirement that spaces should not be next to one another. In a hospital, for example, it may be necessary for the operating theatre and the recovery rooms to be next to one another, but wards for infectious diseases should not be close to either of these.

From this abstract level, where notions of functional spaces, groupings and relationships are considered, there is a move to a more physical level, where more concrete concepts are dealt with. These concepts are represented in the physical design object model.

[31] **Flemming, U, Coyne, R, Glavin, T, and Rychener, M** 'A generative expert system for the design of building layouts – version 2' **J Gero** (ed) *Artificial intelligence in engineering: design,* Elsevier (1988) p 462

6.2 *The physical design object model (Figure 4)*

Overlap between the models is demonstrated by the inclusion of the class 'space' in both diagrams. At this stage, however, this has become a less abstract notion, more tightly defined geometrically, and perhaps also materially. It is suitably defined by British Standard 6100: 'space – area or volume bounded actually or theoretically'.

Various researchers have addressed the issue of structuring information about spaces and their boundaries[13]. In the physical design perspective of the ICON model a space is permitted to have many boundaries, but each boundary delimits only one space. Since spaces are not always separated from one another by physical obstacles (walls, partitions, etc.), but may simply be areas given over to a particular function, the object class 'space separator' is subtyped to allow for both physical and virtual separation. Each boundary may be part of one space separator, whilst each space separator is composed of two boundaries, one from each space. In the case of a physical space separator, its two boundaries are its surfaces. Thus, if we are considering a wall between two rooms, the wall is seen as composed of two surfaces, each of which forms the boundary of one space.

'Boundary' is subtyped using an incomplete partition. Each subtype within the partition is the surface of the physical space separator of which it is a part. Incomplete partitioning is used in this case in order to allow an instance of the supertype not to be an instance of one of its subtypes. This was done on the grounds that, where virtual space separation is concerned, the boundary cannot be its surface element. Incomplete partitioning permits a boundary to be nonphysical. As an alternative, one could introduce the concept of a virtual boundary.

The modelling of the relationships between the subtypes of boundary and those of physical space separator are a further illustration of composition (see Section 4). A wall consists of both surface and structure, and each component has its own component parts, e.g. the structure may be composed of bricks, mortar and plaster. All of these things are aggregated in the concept 'wall', thus reducing complexity.

A space separator may be internal, external or party. An internal wall is one which separates two spaces within a building; an external wall separates internal spaces from the outside; a party wall separates two adjoining buildings. The partitioning is attached at the level of the supertype, rather than the subtype, to allow doors and windows to be described as internal or external. This is important as different characteristics may be required of each: an external door demands adequate weatherproofing and different construction from an internal one.

As already noted, a space separator may be virtual or physical. It may also be an opening. This is modelled using generalization, since this provides for the situation where an instance of the supertype is an instance of more than one its subtypes at the same time, e.g. a door which is both an opening and a physical space separator. With this modelling method it is possible for an opening to contain an opening – a valid option, since it is perfectly possible to have a window in a door or a stable-type door.

The class 'opening' may be further subtyped, using generalization, into such concepts as arch, hatch, door and window. This is not a complete list but is intended to be illustrative. The classification depends on the precise definition adopted in each case. The object-oriented concept of *intersection* is demonstrated in the diagram with reference to door and window. If an instance of opening is an instance of both of these, it is always automatically an instance of French window.

6.3 The structural design object model (Figure 5)

This represents the structural perspective of designing. Here the central concept is 'building element' which, as the figure shows, is linked to the previous model by way, for example, of the object class 'physical space separator'. Whereas the physical design perspective viewed the space separator as the physical representation of a boundary, the structural perspective highlights its properties as a constructional element. It appears now as a subtype of the building element and there is no recognition of any spatial notion.

The reason for the use of generalization rather than partitioning is that it is possible for a physical space separator to be one of the subtypes of building element at the same time as serving the purpose of space separator: a wall is both a space divider and a building element.

'Physical space separator' is also linked to 'building element' via a relationship of composition, indicating that it is always composed of one or more building elements (which do not have to be the ones shown). A building element does not have to be part of a physical space separator, although it is possible for it to be part of more than one.

The model shows two partitionings of building element. One subtype involves the complete partition into structural or nonstructural element.

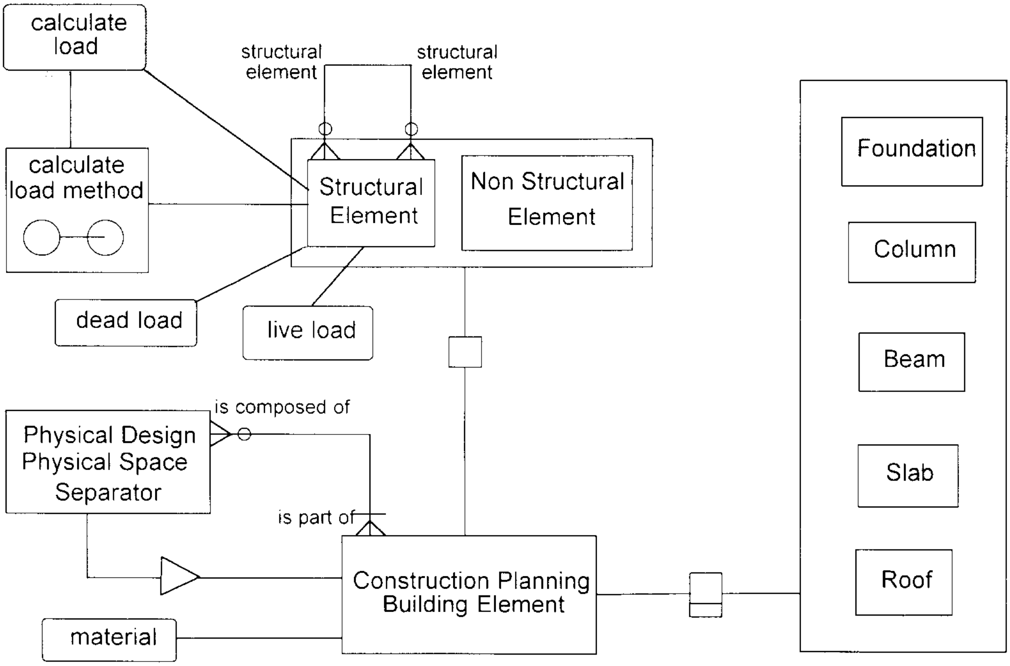

Figure 5 Structural design object model

Each building element must, therefore, be either a structural element or a nonstructural element. If the instance of building element is a structural element, the recursive relationship with itself shows that it may be composed of other building elements or may form part of other building elements.

The second partitioning describes the types of building elements that may exist. The use of incomplete partitioning denotes the fact that this is not an exhaustive list of building elements.

Material is modelled at the highest level, being an attribute of building element. As it is modelled at this level, it is inherited by all of the subtypes and generalizations of the building element.

The operation 'calculate load' is shown in the model attached to the object class 'structural element'. Operations show the activities that can be performed on the object class but hide the complex algorithms that are involved in the computer implementation: this is an example of *encapsulation*. Clearly the same calculation cannot be used for all elements and for all different circumstances. Underlying the one operation 'calculate load', there is a different, and appropriate, method for each type of structural element: this is *polymorphism*.

7 Links with CAD

In the current, and final phase of the project, the possibility of links with existing, commercial packages is being explored. As a demonstration, an interface has been developed between the database implemented according to the ICON design model and AutoCAD, one of the most widely used CAD/drafting packages.

An inherent limitation of most commercial software at present on the market is that it does not have an object-oriented structure. This remains true of AutoCAD, although, in its most recent release (version 12), it is now possible for the points, lines and other features with which AutoCAD works, to be linked directly to a menu of building elements (space, walls, structure, roofs, doors, windows etc.) held in an associated package, AEC. Use of 'objects' of this sort opens the way, in principle, towards a link between graphic information and the specification of components and materials.

To make full use of the functionality of AutoCAD, it would be necessary to tie the object classes in ICON directly to those in AEC. This was found to be impracticable: the objects at present defined in AEC do not correspond to those developed in ICON, and, given the lack of an object-oriented data structure, the operations performed on these are not necessarily those required by the ICON conceptual models. The interface between AutoCAD and the ICON object-oriented database is implemented by way of an 'interface perspective'. This is an object model that contains classes that are subtypes of the conceptual classes described in the ICON models, but which also contain the functionality required to interface to AutoCAD. In this approach the user interacts with the AutoCAD user interface, but the user's actions are intercepted by the ICON system. Menus are provided in the AutoCAD package, which cause objects to be created in the ICON database. These objects are then able to draw themselves on the AutoCAD screen by means of the AutoCAD programming interface. These objects then make the appropriate, corresponding changes to the AutoCAD drawing. Thus such objects as zone, space separator and boundary, are translated directly into AutoCAD primitives, lines, symbols etc.

8 *Conclusions*

It has not been the purpose of this project to unravel the inner workings of the design process, or to pursue the question of cognitive paradigms in design. There is ongoing work in this field[32,33]. Emphasis has been placed here on the identification of design concepts and information structures that are critical in terms of information flow within the construction industry processes. The object models discussed above deal, at various levels of abstraction, with concepts of spatial organization, space separation, zoning and enclosure, which are of fundamental importance, since they underpin cost analysis, construction planning, project management, maintenance, and many other processes that come into play during the life cycle of the project.

In the past, information modelling has been limited by the need to break down activities into discrete areas, and to represent information in terms of the lowest common demoninator among differing views and actors. This can result in very artificial systems of classification, which are liable to damage a very abstract, closely textured and iterative activity such as design. The technique of perspectives used here is thought to represent a considerable step forward, since it allows concepts to be classified and aggregated in the manner most suitable for the requirements of each individual task or process, whilst still adhering to a common underlying information model. A particular advantage is that this approach can cope with different levels of abstraction within the same model, thus allowing high-level concept models, such as that shown in Figure 2, to be developed and integrated with others dealing with much more physical and tangible aspects of design and building. An object class in one part of the model may appear as a subclass of an object class in another. This is facilitated by the use of object-oriented CASE tools, which provide the means to hide or display information as appropriate whilst maintaining the full information model in a central repository.

In the short term we expect to build further interfaces between the ICON models and existing commercial software (e.g. Manifest, Superproject), allowing, where possible, dynamic data sharing to take place between different packages. More broadly, there is a need for further development of object-oriented software to permit better and more consistent handling of very abstract object classes and specific objects in the one model. More intelligent software is also needed to manage information and identify inconsistencies in large information models containing multiple perspectives.

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32 Oxman, R E 'Prior knowledge in design: a dynamic knowledge-based model of design and creativity' *Design Studies* Vol 11 No 1 (1990) 17–28

33 Oxman, R E and Oxman, R M 'Refinement and adaptation in design cognition' *Design Studies* Vol 13 No 2 (1992) 117–134

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