A Process And An Object Oriented Analysis To Integrate Design And Construction

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Abstract

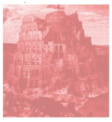
This study is aimed at identifying design related problems encountered by contractors with the intention of minimising them. A full process analysis was carried out on the design function of concrete framed office buildings whereby site problems were traced back to the relevant design information. Design processes that significantly contribute to these problems were highlighted along with their data flows. An Object-Oriented Analysis method has then been applied to model the information in terms of the fundamental ideas that underlie object-oriented technology i.e. object types and classes, methods, requests, encapsulation and inheritance. Proceeding through the five major activities of Coad &Yourdon's OOA method, a complete OOA model has been developed with potential to improve the construction related problems.

Keywords: Design and construction integration, information modelling, process model, object-oriented analysis,

Introduction

Design and construction of buildings in general proceed sequentially, coupled through annotated set of architectural and engineering drawings. Designers do not often anticipate the implications of their design on construction and contractors' interpretation of the design solution often does not meet designers' intentions. This separation of design and construction processes has not only led to the decay of integration but also to a growing misunderstanding of the role of each profession. No other industry sees it practical to disunite the project design from its production. For example, in the manufacturing industry where similar problems exist, successful attempts have been carried out over the last decade to merge design and manufacturing processes. The most widely known approaches in that arena, which bring about a closer link between the design and manufacturing processes are; simultaneous engineering, team design and rapid prototyping (Cutkosky & Tenenbaum, 1990).

Each of the above approaches has its advantages and disadvantages in producing viable solutions. Several systems have been developed to automate and combine the best parts of each approach and to achieve what is known as "Design to Manufacture". They are all based on providing manufacturing knowledge and availability of tools at an early design stage (Cutkosky & Tenenbaum, 1990) (Gupta, et al, 1993)(Henderson & Anderson, 1984) (Chang, et al, 1988). Experience in the manufacturing industry has shown that the implementation of such systems results in generating alternative manufacturable design solutions. It has also shown that such systems do not cripple design creativity, mislead designers with 'myopic' manufacturing views or are only suitable for detailed design (Cutkosky & Tenenbaum, 1990).



In the construction industry, designs with poor integration, accompanied by inadequate detailing and incompetent communication, not only create problems for the constructor, but are also costly and time consuming for both clients and designers. This paper addresses the information required to improve the constructability of the design and suggests a framework for a general tool for designers to use without effecting the flexibility and creativity of the current design methods. An analysis of the design process is addressed with the aim of highlighting the design processes that are a) responsible for the pre-defined construction problems and b) prone to automation. An object oriented analysis technique is also discussed to model the design data at the previously defined processes. The paper briefly discusses the aspect of OOA and it's structured methodologies along with a detail explanation on the implementation of the used methodology.

The Influence of Design on Construction

Previous research has shown that there is a general agreement for the need for integrating design and construction (Adams, 1989) (CIRIA, 1983) (Ferguson, 1989) (O'Connor & Tucker, 1986) (O'Connor & Schultz, 1987). A number of actions have been recommended for consideration by the various parties involved in a project in order to achieve successful integration. Such actions are; simplified designs, standardisation and repetition of design elements, effective communication of design information, dimensional co-ordination of elements, compatibility of elements/materials tolerances, and input to design.

Although designers cannot be solely held responsible for the improvement of such integration, the evidence exists to suggest that they are in a position to play a significant role in improving design-construction integration. Construction personnel, for example, have previously found that most of the site problems are related to poor integration and have been able to suggest alternative solutions (O'Connor & Tucker, 1986) (Polytechnic of Central London, 1984) (Hon, Gairns & Wilson, 1989). Therefore, construction input into the design process is vital and has to be portrayed to designers. This can be fulfilled by an IT based system which can provide designers with inexpensive and fast tool to examine the impact of their design on construction.

Information Modelling

Several attempts have been made to model project's information from its early design stage to construction with the aim of improving design and construction processes (Aouad, et al, 1993) (Ford, et al, 1993) (Fischer, et al, 1993) (Luiten, et al, 1993). All of these attempts have focused on the development of a general and comprehensive model. This study, however, attempts to break down the project vast information into groups of related information which can be easily modelled (Alshawi & Underwood 1994). This will significantly narrow down the involved amount of information and will in turn increase the likelihood of producing practical results. Such grouping will be based on construction problem areas, as highlighted by previous research in this field, i.e. superstructure, substructure, finishing, etc. where each problem area can then be traced back to its design stage. The research focuses on problems related to the superstructure group of reinforced concrete office buildings.

Site problems which can be related to the design process have been identified and traced back to their related design stages. In any construction project there are three main sources of information; client, design team, and contractor. Once design drawings are completed, any design related problems, identified by the contractor, can be traced back to their design stages. Therefore, the information sources that influence such problems are the client and the design team. Whereas the contractor information source, once problems are identified, is incapable of improving on the design. This is an important issue which focuses all the analysis operation on the design team/client. Thus, sources of information can be narrowed down and as a result the likelihood of producing good and practical results is increased. Figure 1 shows the established approach to integrate design and construction. Each group of related information can be channelled down to the design team/client source of information in order to identify the main related design or decisions processes. Solutions coming up from these groups are then integrated into the design process which can highly improve the final product. The following section discusses the methodology that has been followed to identify construction problems related to the superstructure group and how to link them to their related design processes.

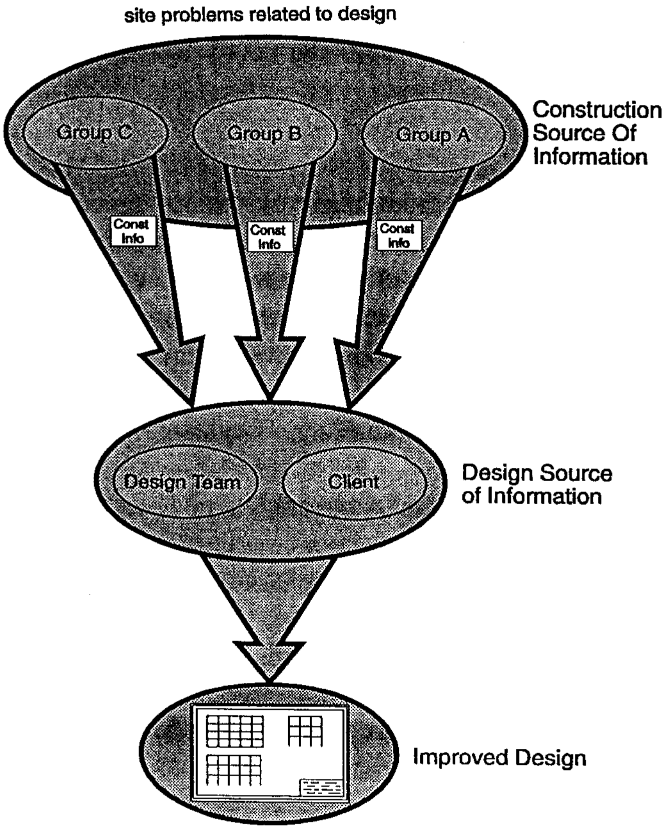


Figure 1: The Established Approach to Integrate Design and Construction

Construction Problems On Site

Semi-structured interviews were held with some of the United Kingdoms largest traditional contracting companies, discussing the design related problems arising on site and how in their opinion the designer can ease contractors executions. The interviewees mainly consisted of site management personnel e.g., site agents, construction managers and construction engineers. Arrangement of the interviews was so that emphasis was directed towards the design related problems, although, the interviewees were instructed to contribute any aspects outside this domain they felt important. Throughout the course of these interviews, various problems and improvement ideas were revealed. They were then analysed and grouped according to their relevance to the design information. These are:

1) Dimensional co-ordination
These problems are related to the ill co-ordination between the dimensions of the adjacent elements. Extra work is created as a result of manipulating an element such as a window, or materials of an element such as bricks to fit some design dimensions e.g. clear span. These problems have been categorised as follows:

(a) Dimensioning of a grid system conceived from brickwork/blockwork dimensions e.g., between columns (horizontally) and beams (vertically).
(b) Dimensioning of a grid system conceived from curtain walling/cladding dimensions e.g., between columns (horizontally) and beams (vertically).
(c) Sizing and positioning of windows and doors to correspond with brickwork/blockwork courses.

2) Tolerances incompatibility
These problems are related to the incompatibility of the tolerances of the adjacent elements. Adjustments of elements, on site, are required when the tolerance of an element does not coincide with the tolerance of the adjacent elements i.e. the interface between different products (elements). These problems have been categorised as follows:

(a) Interfaces between member of the frame e.g. beams to columns/slabs and slabs to columns.
(b) Cladding/brickwork/blockwork interfacing with frame members.

3) Standardisation/repetition of elements/materials

4) Complex designs
The complexity of the construction process increases as the variability between the various design elements increases. Examples of such variability could be:

(a) Grid system with unequal dimensions.
(b) Grid system created from non-modular elements (beams, columns, slabs).
(c) Variable sizes of windows and doors.

Designer's Experience

Several interviews were held with designers, architects and engineers, from either traditional design practices or design and build organisations. These informal interviews were aimed at tracing the previously outlined problems back to their origin in the design process. The objective is to extract the relevant design processes together with their information flows which directly contribute to the creation of the above construction information. Such clear aims and objectives are absolutely vital to the success of modelling the design process as analysts can easily be overwhelmed by the complexity of the design information which can results in an unfocused and complex information model.

During the interviews, the discussion was planned to identify the relevant sources of information, processes and information flows. Initially, these interviews assisted in the establishment of a conceptual information model which reflects the relation between the sources of information with respect to the decision making process, and to the type of information used. This led to the identification of the various parties involved in the decision making process and the responsibility of each to the strategic design decisions. Relevant design process and their information flows were identified and structured. The final stage of the designers' interviews was to confirm the developed process model and to discuss alternative for improving the design. Both of the models are explained in detail in the following sections.

Process Model

A complete system analysis exercise was carried out on the design process with the aim of producing a process model for those processes that are related to the pre-defined construction problems. Data flow diagrams were used to structure the information and their relevant processes. This task was carried out in two stages with relative ease due to the clear objectives of the interviews which are pointed toward certain types of information.

Stage 1:
The first stage of the analysis concerned with the development of the Level 1 diagram of the design process. This diagram shows the highest possible design processes with their information flows, as shown in Figure 2. It reveals three main processes; Architectural Design, Produce Outline Design and Development of Production Drawings along with their input and output. The Architectural Design process takes site conditions and client's brief as its main input and produces crucial information such as frame type, grid layout, number of stories, type of materials, etc. The second main process, the Produces Outline Design is the final process to be performed by an architect after approving the Dimensional Bay Design. The outcome of this process is a complete design outline which mainly constitute the input for the Structural

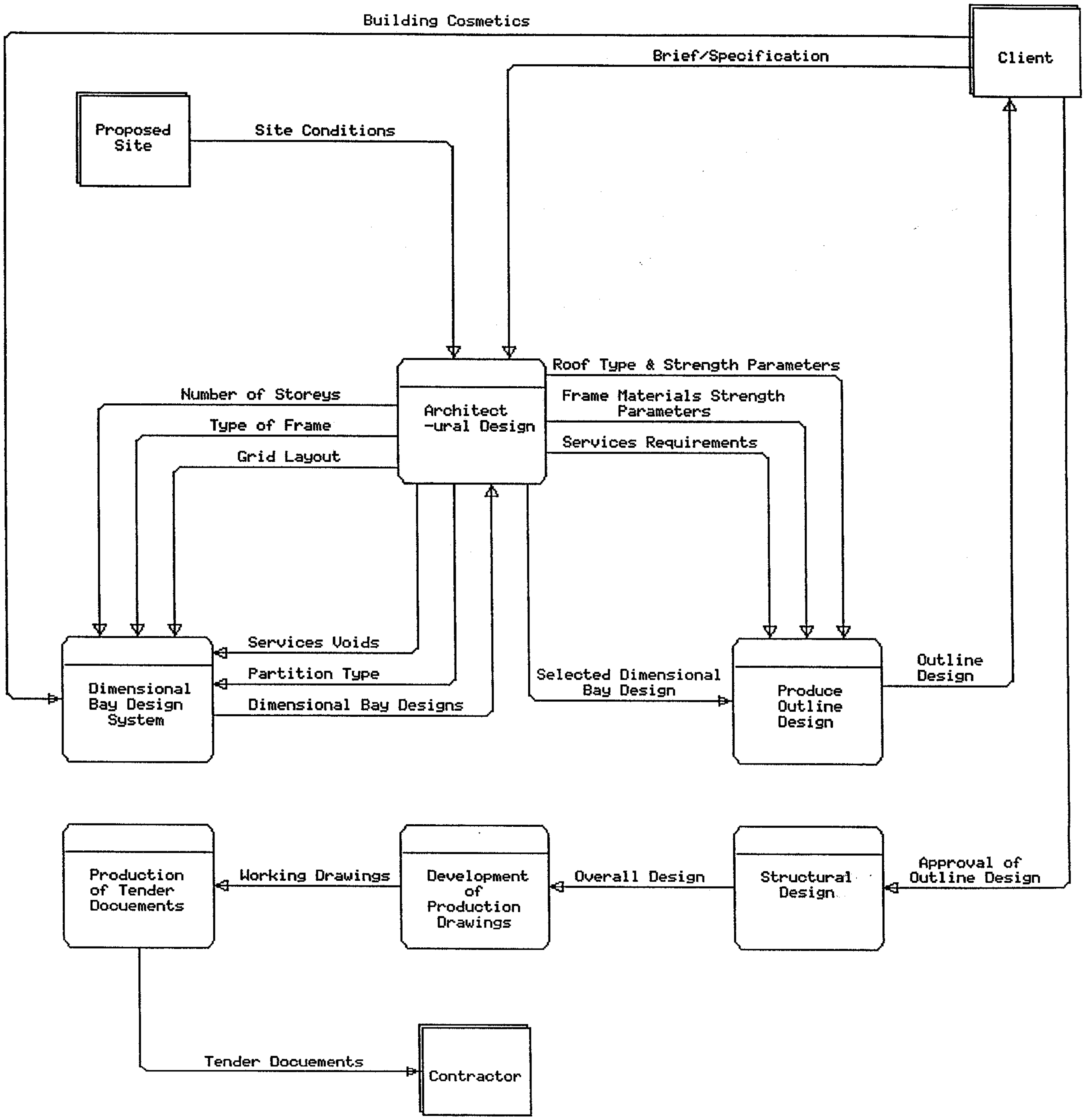


Figure 2: DFD For The Design Process Of R.C Framed Office Building Developments.

Design process. The third main process, Development of Production Drawings, produces detailed design drawings.

Information co-ordination at stage 1

This stage of the analysis has revealed that the information relating to the site problems can be placed into two distinct categories. Information which is controllable, i.e. can possibly be automated, is classified as 'quantifiable information'. The information which is uncontrollable, i.e. difficult to be automated, falls into the band of 'non-quantifiable information'. On this basis, further discussion with the designers on the 'quantifiable information' results in the discovery of several courses of action which could influence the improvement of site problems:

1) Horizontal and vertical adjustments of the frame dimensions i.e. adjustment of the grid layout dimension in the horizontal dimension and the adjustment of the storey height in the vertical dimension.

2) Element consistency .i.e. selection and sizing of elements.

This then led to a possible solution to the previously outlined construction problems. Following the recognition of the possible routes of action for improvement to site problems, the co-ordination of the relevant information showed three major activities to be of importance to the improvement of the design related problems.

1) Horizontal co-ordination: This includes the grid layout dimension which can be adjusted to co-ordinate with the cladding horizontal arrangement, and the column cross-section which can be sized by ensuring that the external wall's horizontal dimension together with the column's cross-section reflects the grid layout.

2) Vertical co-ordination: This include the storey height which can be adjusted, in the vertical plane, and the beam depth which can be sized to correspond to the cladding vertical dimension.

3) Element Information Consistency: This covers the compatibility between factory tolerances of the selected types of cladding and the recommended tolerances of the selected frame type.

Stage 2:

Figure 3 breaks down the Dimension Bay Design process to a further level. The core processes in this diagram (as identified by the information analysis) are the Horizontal Co-ordination of Cladding Types/Beams and Vertical Co-ordination of Cladding Types/Columns. They take in information from a higher level i.e. from the Architectural Design process and Client as well as information generated by other processes in this level such as cladding style, maximum glazed area, British Standards for tolerances, etc. Each of the

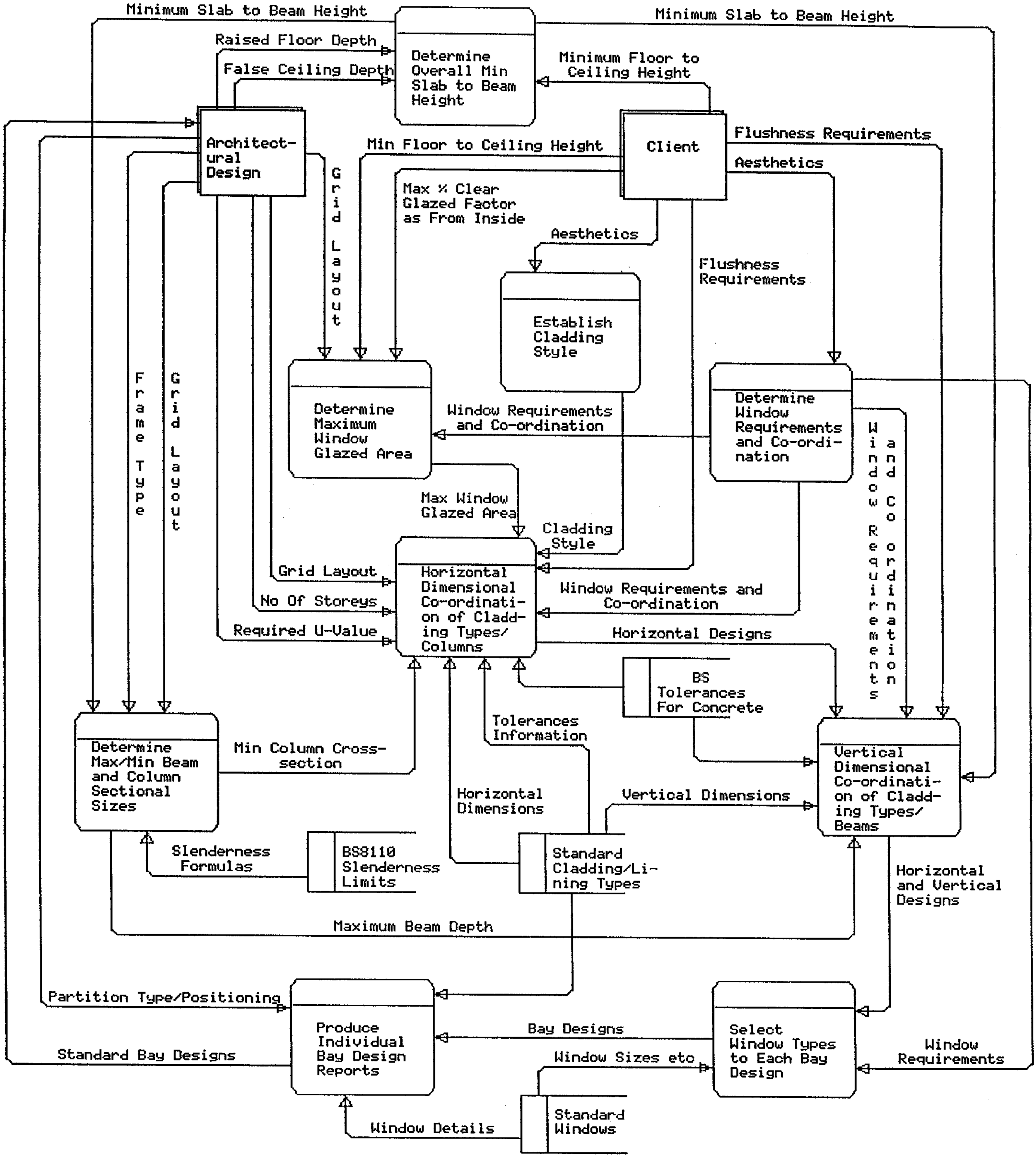


Figure 3: DFD For The Dimensional Bay Design System.

processes aims at establishing consistency in dimensional co-ordination and tolerances of the various elements of a concrete frame. After establishing the cladding style, maximum window glazed area, minimum column cross-section (as given by British Standards), etc., the Horizontal Dimensional Co-ordination process adjusts the horizontal dimension of the original grid layout and sizes the column cross-section in order to reflect the horizontal arrangement of the cladding/lining elements. The Vertical Dimensional Co-ordination process adjusts the storey height dimension and sizes the beam depth to ensure correspondence with the cladding/lining elements vertical arrangement. The construction tolerances for the frame in both horizontal and vertical directions are checked for consistency with the factory tolerance of the cladding type. The outcome of this process is an adjusted building dimension layout (grid layout, storey height) and the sizing of frame elements, which altogether improve quality and reduce construction problems.

Single Bay Design Solution

The information analysis has resulted in solving the problems relating to the dimensional co-ordination and tolerance incompatibility information aspects. However, in order to enhance the standardisation/repetition of elements/materials and the simplification of design the spatial arrangements design for mid-rise reinforced concrete office projects can be perceived as a single bay design exploited repeatedly to form the project arrangement. From this notion, it is therefore seen beneficial for an individual bay to be designed for from standard available elements (cladding, masonry, windows etc.) and including frame member sizes, which employed repeatedly will form the complete spatial arrangement of a project (Figure 4).

As the Dimensional Bay Design process basically entails going through 'structured' procedure, it is envisaged that this process can be automated. In order to automate this process a data model is required to map its information into a structured model. This study has implemented an object oriented analysis to model such information.

Object-Oriented Analysis

The objective of OOA is to heal the contemporary divide between process analysis methods and data analysis methods (Beynon-Davies, 1991). The deficiencies of each of the contemporary approaches to information systems development are highlighted by the proponents of OO. For process analysis methods based around such techniques as data-flow the functional or dynamic side of information systems is over-emphasised whilst, the structural or static side is under-emphasised. On the other hand, data analysis methods based on such techniques as entity-relationship over-emphasise data and under-emphasise process.

In addition, Object-Oriented Analysis provides several motivations and benefits (Yourdon & Coad, 1991). Extra emphasis is brought to the understanding of problem domains enabling more challenging problem

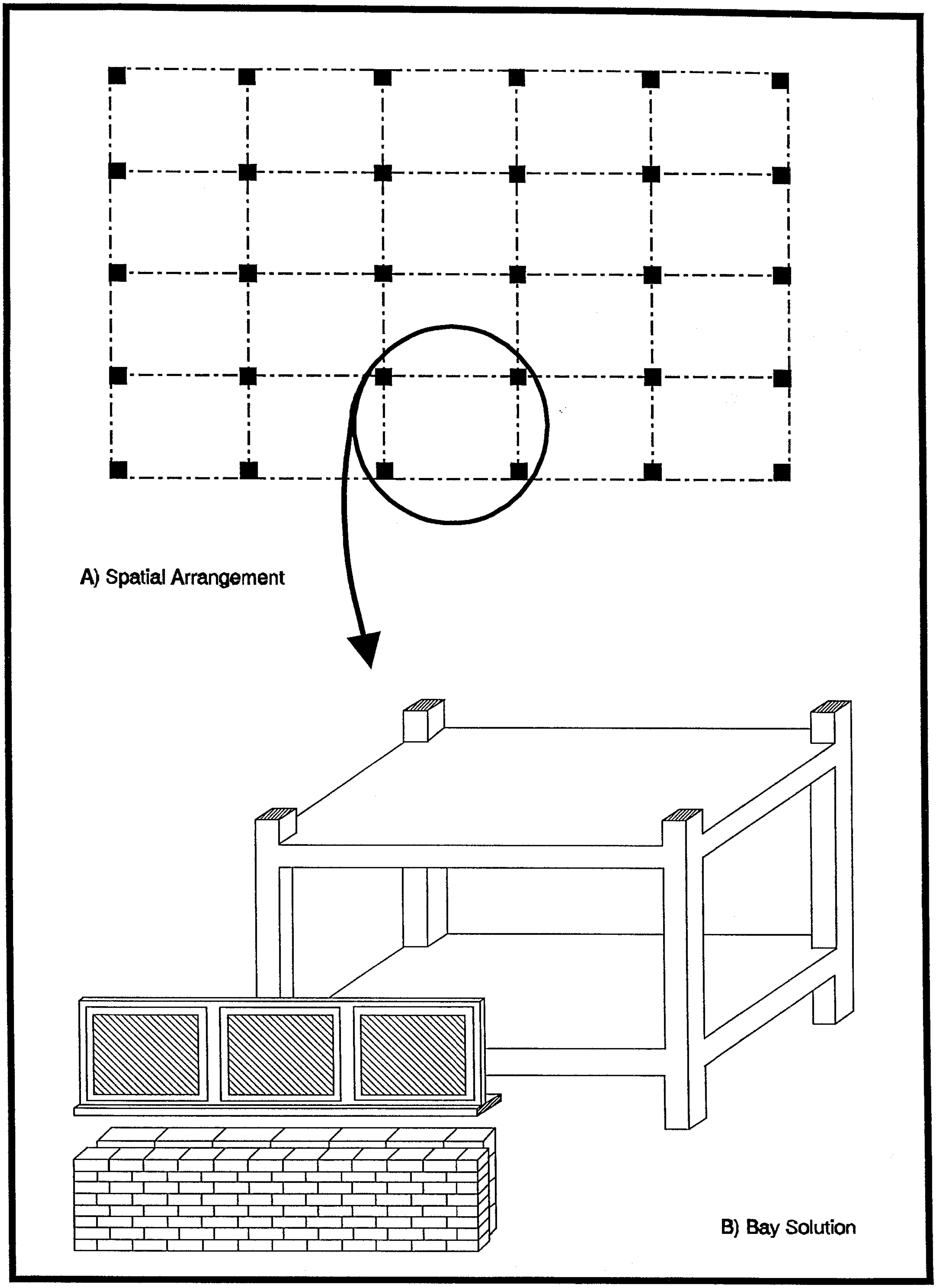


Figure 4: Spatial Arrangement Design and Bay Design Solution

domains to be tackled. System analysis and specification are organised using the methods of organisation which pervade people's thinking. The internal consistency of the analysis's results is increased, i.e. the bandwidth between different analysis activities is reduced, by treating objects' attributes and behaviour as an intrinsic whole. Moreover, inheritance identifies and capitalises on commonalty of the latter. While, specifications are built resilient to change with volatility being packaged within problem-domain constructs, providing stability over changing requirements and similar systems. Results based upon problem domain constructs are organised for both present and future reuse. A continuum of representation, for systematically expanding analysis results into a specific design.

Object-Oriented Analysis: Structured Methodologies

The overall approach of OOA, consists of either four or five major activities, depending on the OO method of analysis. These are activities and not sequential steps. They guide the analyst from high levels of abstraction to increasingly lower levels of abstraction. For example, Coad & Yourdon's method of OOA proceeds through five stages resulting in the development of a complete OOA model presented and reviewed in five layers. These layers being much like overlapping transparencies gradually presenting more and more details.

The fundamental concepts that form the basis of object-oriented analysis include: object types and classes, methods, requests, encapsulation and inheritance. An object is an abstraction of a set of real-world things, about which we store data and those methods that manipulate the data. Classes specify data structure and the permissible operational methods that apply to each of its objects. Methods determine the way in which an object's data are manipulated. The methods in an object type reference only the data structure of that object type. Should they wish to access the data structure of another object, they must send a request (message) to that object. Encapsulation or "information hiding" is principle used to reveal as little as possible, the inner workings of an object to its user. Inheritance is a mechanism which expresses similarity among object types. A high level object type can be specialised into lower level object types.

Object-Oriented Analysis

This sections describe the implementation of Coad & Yourdon's OOA methodology to model the information related to the above mentioned processes (Alshawi & Underwood 1994). The five steps involved in this methodology are:

1. Finding Class-&-Objects

The first stage in the OOA is to identify classes and objects. The primary motivation for identifying Class-&-Objects is to match the technical representation of a system more closely to the conceptual view of the real world. A Class-&-Object is represented by a bold rounded rectangle, divided into three horizontal sections and surrounded by a light rectangle. A class is represented by a bold rounded rectangle divided into three horizontal sections. The class name is positioned in the first horizontal section (Figure 5). Some of the Class-&-Object defined were; the Horizontal Co-ordination of Cladding Types/Columns and Vertical Co-ordination of Cladding Types/Beams, Grid Layout, Structure To Structure Height, Cladding Style and Lining Requirements, Flushness, Frame Type, Column Slenderness, etc.

2. Identifying Structures

Identifying Structures focuses attention on the complexity of multiple Class-&-Objects. In Coad & Yourdon's method of analysis, two types of structure (relationship) are recognised; a Generalization-Specialization (Gen-Spec) Structure, and Whole-Part structures i.e "kind of" and "part of" structures. Some of these structure that the analysis has produced are; Cladding class as Gen-Spec Structure, Horizontal Co-ordination and Vertical Co-ordination Class (Horizontal Exposed Co-ordination, Horizontal Unexposed Co-ordination), (Vertical Exposed Co-ordination, Vertical Unexposed Co-ordination), Frame Type as a Whole-Part structure where Beam and Column Class-&-Objects are part of, etc. Figure 5 a-d shows such relationships.

3. Identifying Subjects

Subjects are strictly a means to an end, they give an overview of a larger OOA model. The principle basis for identifying Subjects is problem domain complexity. The Subject layer of the model helps a reader review the model, concisely summarising the subjects within the model. The analysis resulted in the identification of four Subjects, as shown in Figure 6. These are:

1) An Architect Subject which covers information required by the Horizontal and Vertical Co-ordination objectives i.e. information provided by the design team.

2) A Database Subject which represents the process of selecting cladding and lining types.

3) A Design Subject groups the information related to general design issues.

4) A Bay Designs Subject includes the modelled information for producing and presenting outputs from the core processes.

4. Defining Attributes

Attributes add detail to the "Class-&-Object" and "Structure" abstractions. Such details describe values which are kept within an object, to be exclusively manipulated by the Services (behaviour/processing) of that object. For example, the horizontal and vertical dimensions of cladding are required

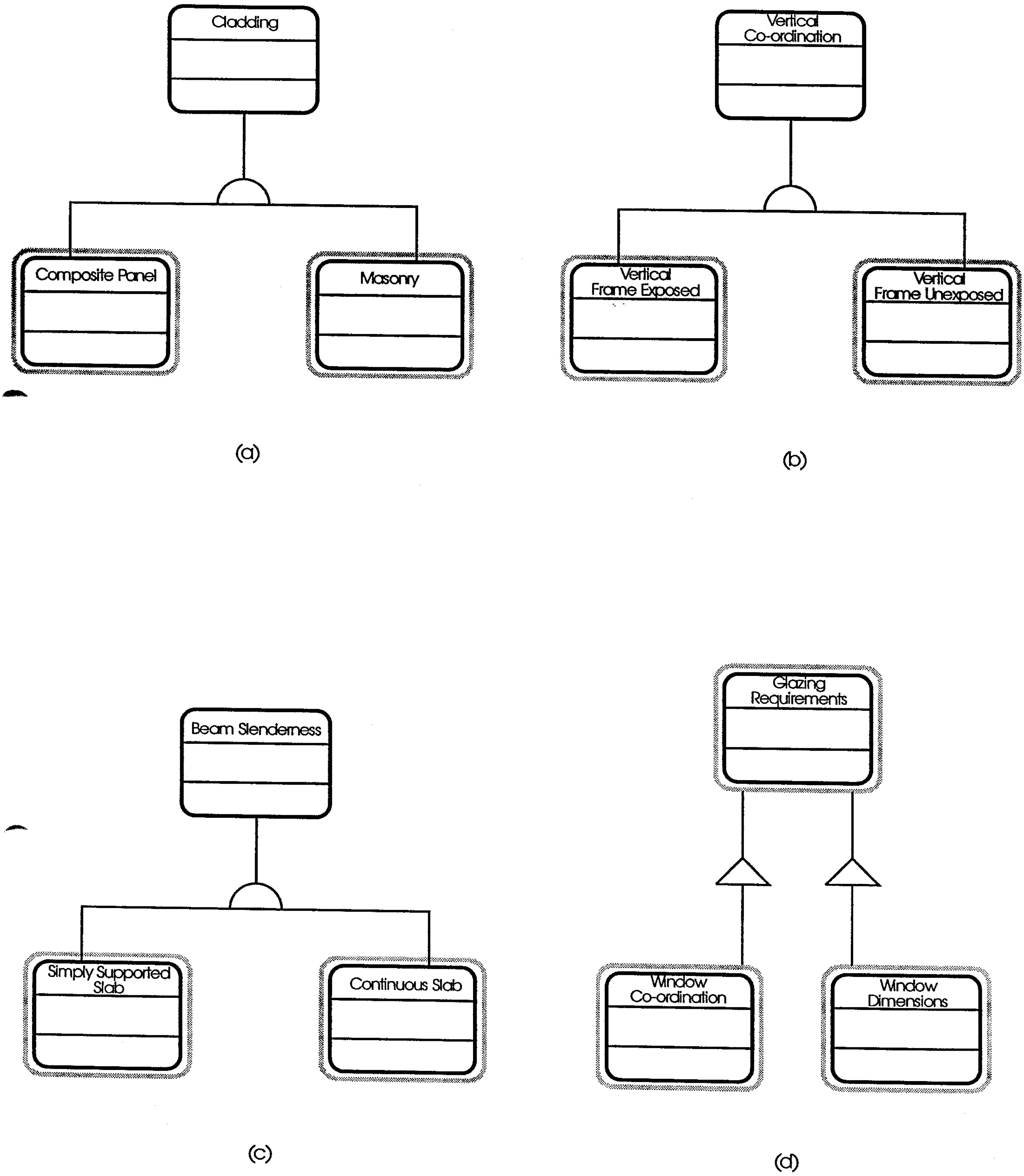


Figure 5: Samples of Structure Layers.

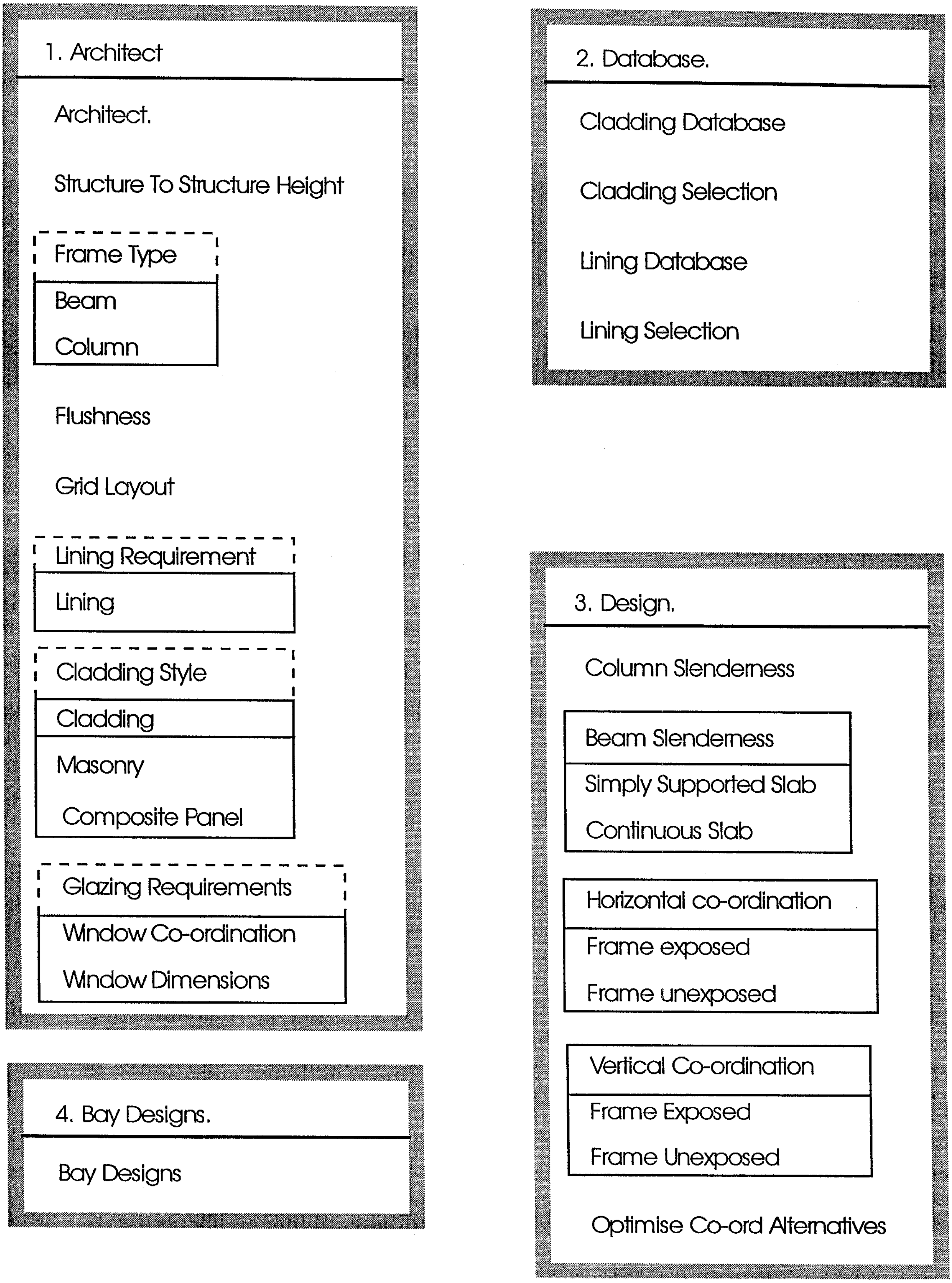


Figure 6: Partially Expanded Subject Layers.

before the core processes can carry out their assigned functions. The attributes were identified by finding what an object in a class is responsible for knowing with respect to the problem domain, positioning attributes within the Class-&-Object which best described it, and adding instance connections. The latter adds to the Attributes with required mapping needed by an object to fulfil its responsibilities. An Instance Connection is represented with a line between objects showing the dependence between one object's needs and another in order to accomplish its responsibilities. Figure 7 shows Instance Connections between Class-&-Object within and among three Subject layers. For example, Instance Connections are shown between the Glazing Requirement Class-&-Object , at the top of the Figure, and the Column, Grid Layout, and Structure to Structure Height Class-&-Objects. This illustrates that during the Glazing Requirement Class-&-Object processing, this Class-&-Object needs to ensure the column cross-section, grid dimensions and vertical heights are determined before it can accomplish it's goals.

5. Defining Services

In the final activity of the analysis, a detailed description of the system's processing and sequencing requirements are developed. Services further detail the abstraction of the reality being modelled, indicating what behaviour an object within a class will provide. The Services were defined by identifying object states i.e. defining the values of Attributes within an object, identifying the required Services, and identifying Message Connections. Services are classified into two groups; algorithmically-simple ones and algorithmically-complex ones. Algorithmically-simple Services are "implicit" and are not explicitly shown on the Service layer such as Create, Connect, Access, and Release. Algorithmically-complex Services, on the other hand, are "explicit" and are explicitly shown on the OOA Service layer such as Calculate, and Monitor.

Message connections map one object to another, in which a "sender" sends a message to a "receiver", to get some processing carried out. The notation for a Message Connection is a light arrowheaded line which points from the sender to the receiver. Figure 8 shows Service layer for Architect, Database, and Design subjects. The arrow denotes a sender "sends" a message; the receiver "receives" the request; and the receiver then takes some action before returning a result to the sender.

Conclusions

The superstructure of reinforced concrete constructions, is recognised to hold many problems due to the poor integration of design and construction, while, designers are seen as being in a position to play the most significant role of improving these problems. This paper has described the study aimed at providing a solution to improve the integration between design and construction for mid-rise reinforced concrete office developments using an information analysis approach.

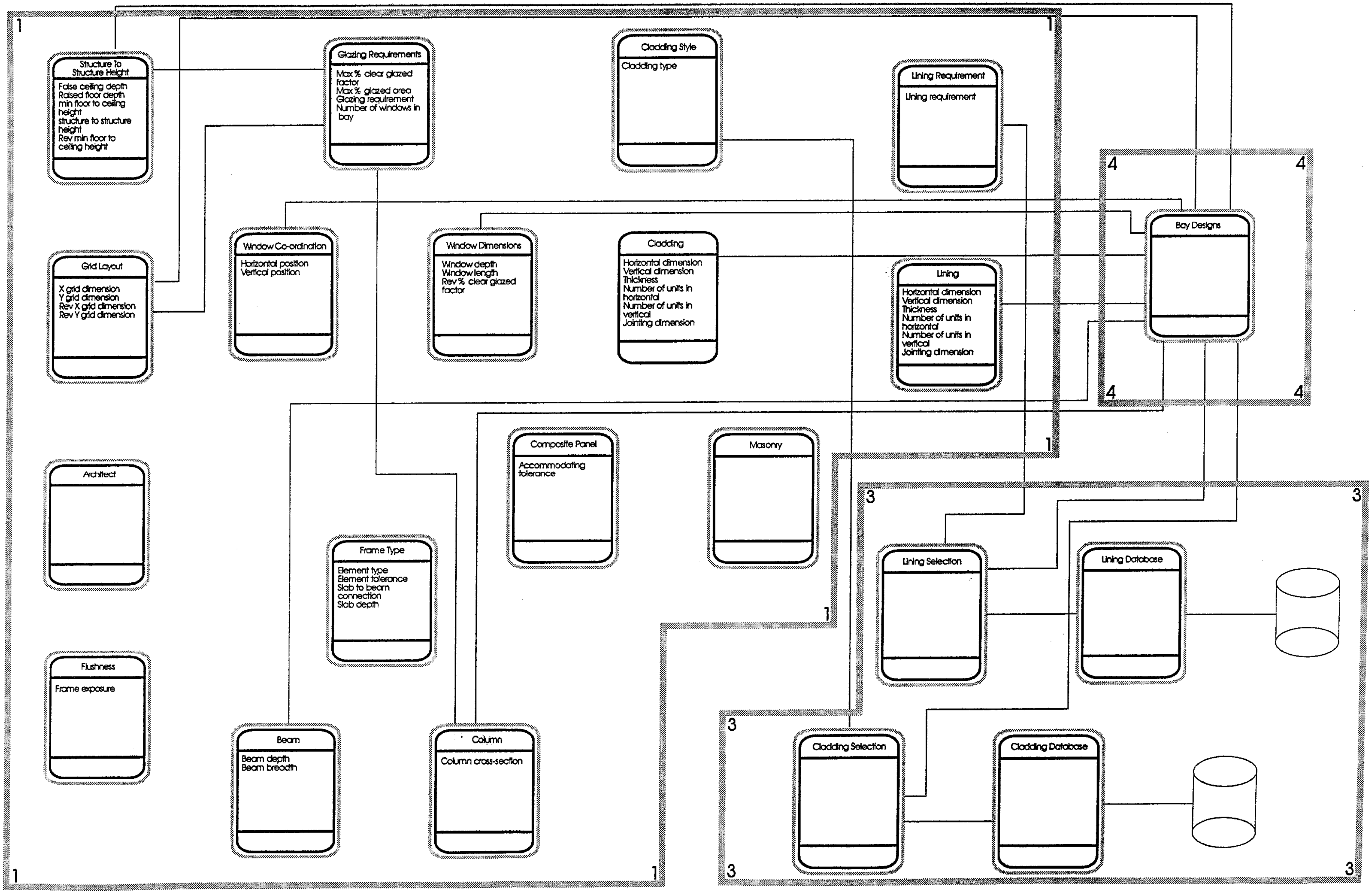


Figure 7: Attri[illegible]te Layer for Architect, Database and Bay Design[illegible]bjects.

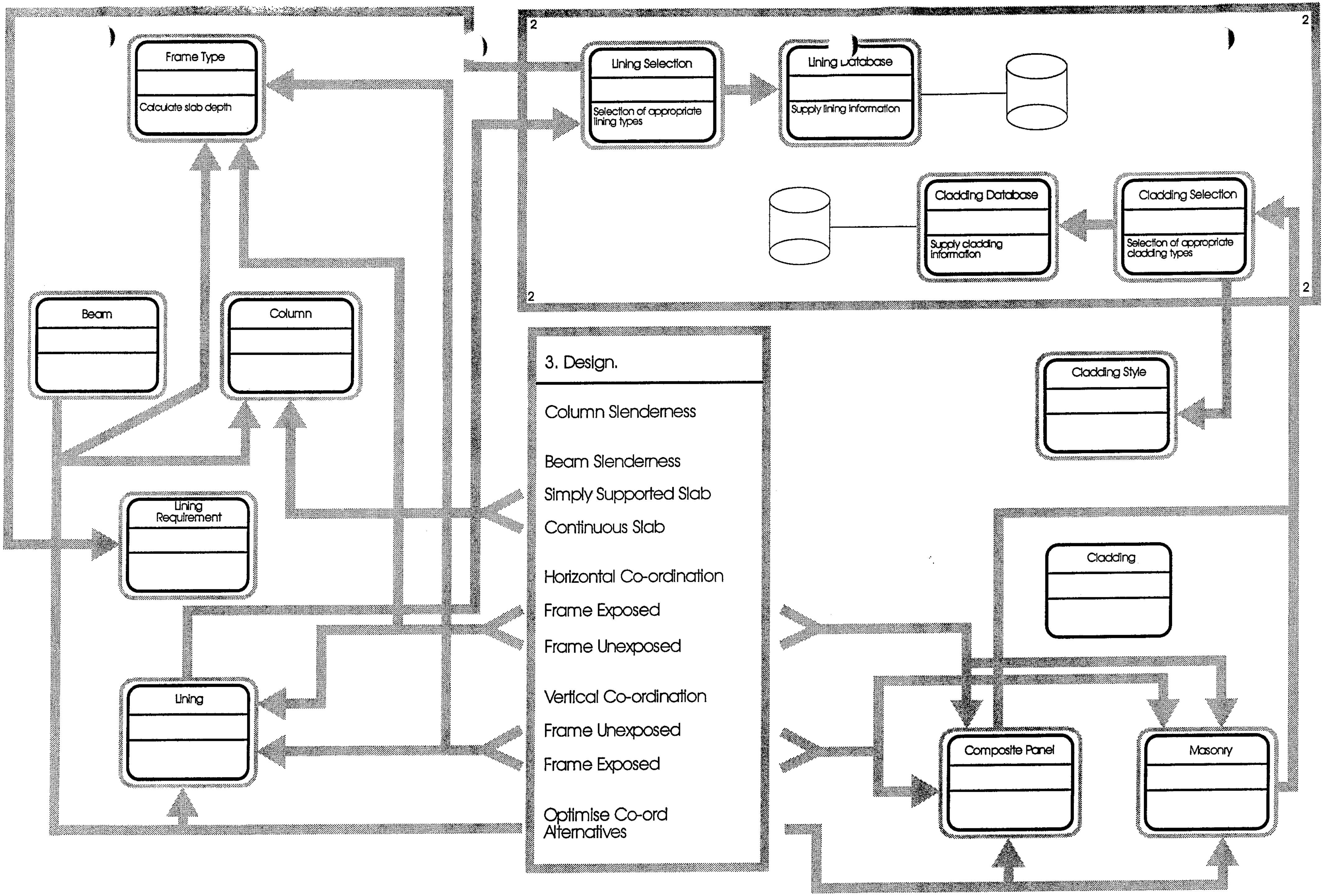


Figure 8: Service Layer for Architect Subject and Database Subject.

Contractors were interviewed to identify the common design-related problems and a full process analysis was carried out on the design process with the aim of tracing the raised construction problems back to their design stages. The core design processes that significantly contribute to the identified construction problems were highlighted along with their data flows. The data were then modelled using a structured OOA, i.e. Coad & Yourdon's, methodology. A five layered model was developed.

The OOA approach has proved to be very successful in modelling processes and data simultaneously. The modelling process has focused on the core data without neglecting the process thus, achieving more effective and consistent model. The overall OOA model is now in a position where mapping into an object-oriented development environment could easily be carried out, leading to the development of an automated integration tool for designers.

References

Adams, S. (1989), Practical Buildability, CIRIA, Butterwoths, London.

Alshawi, M., and Underwood, J. (1994), Information Analysis Approach For Integrating Design and Construction, prepared for publication in Engineering, Construction and Architectural Management.

Alshawi, M., and Underwood, J. (1994), Applying Object-Oriented Analysis to the Integration of Design and Construction, sent for publication in Automation in Construction.

Aouad, G., Kirkham, J.A., Brandon, P., Brown, F., Cooper, G.S., Ford, S., Oxman, R., Sarshar, M. & Young, B. (1993), Information Modelling in the Construction Industry - The Information Engineering Approach, Construction Management and Economics, **11**(5).

Beynon-Davies, P., (1991), Knowledge Engineering For Information Systems, McGraw-Hill Books Company, London.

Chang, .T.C., Anderson, D.C., and Mitchell (1988), OR, QTC- An Integrated Design/Manufacturing/Inspection System for Prismatic Parts, Computers in Engineering, Vol. 1, 417-426.

Construction Industry Research and Information Association (CIRIA) (1983), UK. Buildability : An Assessment, Special Publication (CIRIA) No 26, (Commercially published monograph; 150 Monographic Series).

Cutkosky, M.R. and Tenenbaum, J.M. (1990), A Methology and Computational Framework for Concurrent Product and Process Design, Mechanism and Machine Therory, **25**(3), 365-381.

Fischer, M., Betts, M., Hannus, M., Yamazaki, Y. and Laitinen, J. (1993), Goals, Dimensions and Approaches for Computer Integrated Construction, Management of Information Technology for Construction, World Scientific Publishing Co, UK, 421-433.

Ferguson, I. (1989, Buildability in Practice, Mitchell's Professional Library, London.

Ford, S., Aouad, G., Brandon, P., Brown, F., Child, T., Cooper, G.S., Kirkham, J.A., Oxman, R. & Young, B. (1993), The Object Oriented Modelling of Building Design Concepts, Accepted for publication in Building and Environment.

Gupta, S.K., Nau D., and Zhang G. (1993), Generation of Machining Alternatives for Machinability Evaluation, NSF Conference Proceedings, January, Charlotte, NC.

Henderson, M.R., and Anderson, D.C. (1984), Computer Recognition and Extraction of Form Features: A CAD/CAM Link, Computers in Industry, No. 5, 329-339.

Hon, S.L., Gairns, D.A., Wilson, O.D. (1989), Buildability : A Review of Research and Practice, Australian Institute of Building Papers, Vol 3, 101-118.

Luiten, G., Froese, T., Bjork, B.C., Cooper, G., Junge, R., Karstila, K. & Oxman, R. (1993), An Information Reference Model for Architecture, Engineering and Construction, Management of Information Technology for Construction, World Scientific Publishing Co, UK, 391-406.

O'Connor J.T., Rusch, S.E., Schultz, M.J. (1987), Constructability Concepts for Engineering and Procurement, Journal of Construction Engineering and Management, ASCE, **113**(2), 235-248.

O'Connor, J.T., Tucker, R.L. (1986), Improving Industrial Project Constructability, Journal of Construction Engineering and Management, ASCE, **112**(1), 69-82.

Polytechnic of Central London (1984), Problems of Buildability : Their Prevalence and Solutions, Final Report to the Construction Industry Research Information Association (CIRIA), Department of Building, RIB Research Group, London.

Yourdon, E., and Coad, P., (1991), Object-Oriented Analysis, Yourdon Press Computing Series, New Jersey, USA.