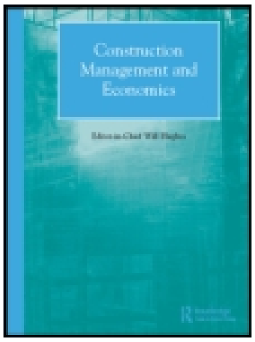

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This paper reports on recent research the aim of which was to study, model and simulate the information flow at the conceptual and schematic stages of building design. The development of a generic model of the conceptual and schematic design process for buildings is described. This model comprising design tasks and their information requirements was produced using data flow diagrams. Examples from several levels of the model are provided. Details are then given as to how the model may be used to assist the management of the design process both directly and by providing primary data for other tools and techniques. Industry feedback on the data modelling and these tools and techniques is then discussed. It is concluded that it is only by a better understanding of the flow of information among project participants that the management of design may be improved, and that although the generic data flow model provides immediate benefits to design managers these can be enhanced greatly by the use of the model as a primary data source for other tools and techniques including the design structure matrix and simulation.

Keywords: Conceptual and schematic design, information flow, data flow diagrams, design structure matrix, simulation

Introduction

In the highly competitive construction market, designers and contractors must respond swiftly and efficiently to clients' requirements and provide a building that meets agreed standards and satisfies cost and time constraints. Efficient management of the design process is imperative to ensure that the clients' requirements will be met before starting construction. Interference in the construction process resulting from design changes or the late supply of information to the construction team is costly. Non-existent or ineffective design management results in extended design timescales. It may also produce conflicting construction details that result in delays and problems during construction (McGee, 1992).

The research described in this paper focuses on the design of buildings. We are interested in design at a contextual level, as a process that requires specific inputs to produce a set of agreed outputs. We define building design as 'a process which maps an explicit set of client and end-user requirements to produce, based on knowledge and experience, a set of documents that describe and justify a project which would satisfy these requirements plus other statutory and implicit requirements imposed by the domain and/or the environment' (Hassan, 1996). This definition recognizes the pre-requisite inputs and outputs of design. It requires consideration of the interfaces of design, i.e. the transfer of design information between the participants involved. It is not concerned primarily with the thought process of the designer or the manner in which specific design tasks are executed. Attention is focused on the exchange of information, the 'fuel of design', necessary for members of the design team to complete their tasks. Although it is recognized that this exchange of information is only one aspect of the management of the design process, the writers consider the management of this information exchange to be critical.

The construction industry has increasingly come to recognize the need for more effective information transfer between participating organizations and internally, among the personnel within organizations (Ndekugri *et al.*, 1988, Gray *et al.*, 1994; Newton, 1995). Methodologies developed by the software industry for systems analysis and design purposes have proved valuable in the study of information flow within construction organizations. Several of these are based on the use of data flow diagrams (DFDs) which map the information flow in a system and record its transformation and coordination (Fisher, 1990; Austin *et al.*, 1994, 1996a). This modelling approach is different from many other descriptive and prescriptive models of the design process (e.g. RIBA, 1973; Cross, 1984; Pahl and Beitz, 1988; Powell and Newland, 1993; Dias and Blockley, 1994) in that these address the different stages of design and their associated activities, but not the information exchange between activities.

This paper reports on recent research the aim of which was to study, model and simulate the information flow at the conceptual and schematic stages of building design. The objectives of the research were to define and analyse the information exchange processes between design, construction and client personnel and to investigate new tools and techniques for planning and scheduling design activities. The basis of this research and the development of these techniques is a generic model of the conceptual and schematic design process for buildings. The development, verification and validation of this model are described in this paper. This is followed by an outline of how data from the model may be used to simulate the information flow processes dynamically to identify critical data, mistiming of data, and the impact of design changes. A detailed discussion of the simulation work is given elsewhere (Baldwin *et al.*, 1998). Industry feedback on the model and the planning tools and techniques produced is presented also.

Building design management

Introduction

The design of a commercial, industrial or other complex building is a multi-disciplinary task requiring input from architects, civil and structural engineers, and building services engineers. To manage the design process effectively it is necessary for the design manager to be sympathetic to the designers' ambitions and method of work, while establishing a framework within which the tasks and objectives are kept in focus as the design moves through its stages of development (Gray *et al.*, 1994). Irrespective of whether the designers are employed by one or several organizations, some form of information management is required to ensure that the participants within the design process meet their commitments in an efficient manner. Information inputs must be scheduled to meet the requirements of each member of the design team. Deliverables must do so within a time scale and at a cost acceptable to the client and all related parties. Information needs to be exchanged in a timely and effective manner. It is the efficient and effective management of this information flow and the resources required to produce the design deliverables, (drawings, specifications, calculations, reports etc.) that we consider essential to improved design management: in particular the interfaces between members of the design team (including the client).

The importance of improved design management is now widely recognized. A report by NEDC showed that more than 50% of problems on building sites were related to poor design information (NEDC, 1987). Frequently these problems were found to be more significant than those attributed to poor workmanship and site management. With the costs in Europe of rectifying building failures running at 12–15% of total construction expenditure (Cornick, 1991), the rewards for improving the management of design information are great. The British Standard, BS7000: *Guide To Managing Design In Construction* (BSI, 1994), recognizes both the importance of the task and the procedures involved.

In the building industry design management traditionally has been the task of the architect, because this profession was first involved with the production of the design brief, and thereafter became involved in the selection of the other design organizations (e.g. structural and building services engineers). It is still normal for the architect to have the lead role in both the design and the management of the design at the conceptual and schematic design stages. All the projects studied within our research were architect led. No attempt was made to widen the research to include projects designed under other forms of procurement, partly because all those interviewed considered the design information requirements to be the same irrespective of the form of procurement.

Management problems

Previous construction related design research, (see, e.g. Topalian, 1979; Ahuja, 1984; Bennett *et al.*, 1988; Gray *et al.*, 1994; Price, 1995) has identified many of the problems of building design management. An early part of the research involved a survey and interviews with twenty construction industry professionals to investigate current practice in building design management and its associated problems (Hassan, 1996). These professionals, who included architects, structural engineers, and building services and other design staff, identified some of their main problems in design management as being due to: (i) the inherent nature of design in particularly its iterative nature, (ii) acquiring technical information; (iii) client changes; (iv) difficulties in managing information (such as the problem of missing information); and (v) difficulties in planning and scheduling design work. Of these categories the last two were considered by the industry representatives interviewed to be of particular significance and within their sphere of influence. These formed the focus of our research. These two categories are directly linked and this focused the attention of the research team on information transfer, communication issues and interfaces, and the development of tools and techniques to assist those involved in the management of the design process. Design is, by its nature, an iterative process, and it is this aspect that makes it complex and difficult to manage. Current planning techniques such as network analysis and PERT are suitable for planning activities which are either sequential or parallel, but cannot be used to plan iterative activities (such as design) because they do not allow feedback loops. Hence the need for new tools and techniques.

The survey and interviews highlighted some problematical information related events, including: starting a design task earlier than anticipated based upon assumed information; gate keeping (or withholding of design information) among design team members; predicting the impact of changes in design information; assessing the result of missing information; evaluating the variation in the quality of information exchanged between different design tasks; and releasing the information from different design tasks in packages or phases. By understanding and making allowance for such events it should be possible to improve the management of information flow, and hence the prospect of completing designs to the time schedule required by the construction team. Clearly, any solution of these difficulties requires some model of the design process and the information flow therein.

Modelling the building design process

Design process models reflect the focus of their researchers. Some are descriptive, describing sequences of activities that typically occur (e.g. French, 1985). These models reflect the solution focused nature of design thinking, showing the process by which design decisions are reached. Others are prescriptive, in an attempt to persuade or encourage designers to adopt improved ways of working (e.g. Cross, 1991). The models of Frost (1992) and Powell and Newland (1993) concentrate on the human and behavioural aspects of designers. The ‘blackbox’ approach of Addis (1990), concentrates on the inputs and outputs of the design process rather than the process itself. Dias and Blockley (1994) have produced integrated product and process models for design through the definition of generic units called ‘roles’. These allow both functions and responsibilities of designers to be identified.

The building design process is a multi-disciplinary process, performed in a series of iterative steps to conceive, describe and justify increasingly detailed solutions to meet the needs of the client. This may be considered to commence with the initial inception of the development and to end when construction is complete. There is no universally accepted model of the building design process. The most commonly recognized and accepted prescriptive model for a building project in the UK is the RIBA Plan of Work (RIBA, 1973). This is a framework of stages from A to M describing all the design work and management tasks within a project programme from inception to completion. The three main stages of design formalized by RIBA are: stage C (outline proposals); stage D (scheme design); and stage E (detail design). These stages overlap with the earlier stage B (feasibility), and the later stage F (production information).

However, this model, widely used and accepted, is deceptive in that the boundaries between the stages are frequently more ‘fuzzy’ than it implies. Also, different forms of procurement and client requirements often lead to the early stages being combined and to variations in the model. BAA plc, a major client of building and construction work in the UK, has developed its own building process model with the intent to clarify and detail all the stages of design, construction, and operation relating to its types of projects.

Modelling the building design process currently is attracting particular attention from researchers because of the need to explore relationships between organizations, study and improve business processes, and benchmark best practice. The approaches adopted include traditional work study methods, process control methods, simulation, and business modelling techniques.

Modelling the overall design process is a hugely complex task. Partial models identifying the detail required by specific user groups are better suited to research purposes. The authors consider existing models of the building design process inadequate for the purposes of understanding information related events and planning and scheduling design tasks, as they do not address the interrelationship of design activities and the information flow between design activities. We argue that it is only by taking these factors into consideration that it will be possible for the design manager to improve the planning and scheduling of design tasks significantly.

Due to the popularity of the RIBA Plan of Work and its universal familiarity the research team decided within the context of this research to consider the design process as consisting of the three main RIBA stages, C, D, and E. However, it is noted that, in practical terms, design professionals commonly are more comfortable with the term, 'concept design', in lieu of 'outline proposals' for stage C and the term 'schematic' as common as 'scheme design' for stage D. The research described in this paper focuses on a data flow model for the concept and schematic stages of design. The development of similar models for detail design is described in Austin *et al.* (1995, 1996a,b).

Development of a conceptual and schematic data flow model

Methodology

The information requirements at the conceptual and schematic design stages were investigated by monitoring design at the conceptual and schematic stages on three large building projects. This involved the observation of the design process, attendance at regular design meetings and interviews with architects, structural engineers, mechanical and electrical engineers, civil engineers and other specialist design staff. The production of the model was an iterative process. The initial version was produced on the basis of three case studies. The model was verified against each of these situations, and then validated by interviews with other architects and engineers from ten different design organizations. The conceptual design stage of a major building project was then 'shadowed' to test the model and the findings presented during a seminar attended by senior design managers. Table 1 outlines the types of project investigated.

Table 1 The types of project investigated

Project	Building type	Procurement method	Value (£M)
A	Power plant	Design and build	110
B	Factory	Design and build	3
C	Engineering complex	Design and build	14

The first case study (A) was an historical study of a completed project. This comprised an initial study from the project documentation, which included: geotechnical reports; environmental statement; scope of work document; progress reports; minutes of meetings; programmes; quality records; team responsibilities; a history of events affecting the design programme; and the preliminary design document. Some of the information needed had to be obtained from members of the design team. This was collated by interviews with key team members. From these data the information flow model was constructed and demonstrated to members of the team who verified the model after requesting some minor refinements.

This initial study provided two important findings. First, it confirmed that data flow diagrams were a suitable technique for information transfer representation (see below). They enabled the research team to identify the key information flows, and this was understood readily by all the personnel involved in reviewing the project. Second, building data flow models from completed projects does not always reveal how and when information is transferred and does not show which design tasks are suspended waiting on information from other tasks. This can be obtained only from shadowing 'live' projects.

The subsequent case studies (B,C) were on live projects. In each case, following an initial interview with the project manager, the researcher attended weekly design meetings and acted as an observer/recorder. This provided direct experience of all the discussions, issues raised, information required, and information issued by designers representing the different disciplines. No other interaction with the members of the design team took place. This decision was taken so as not to cause any disruption to the design team, as the design programmes were very tight. For the same reason, no interviews were conducted with members of the design team during the design phase. However, interviews, where appropriate, were conducted after the completion of the design work.

In addition to observed and recorded information from the weekly design meetings, other sources of information used by the research team were: the scheme design report; the programmes for the design and construction work; and written instructions from the client. In none of the three case studies involved in the development of the model was it possible to interview client representatives on a regular basis. Within the model produced there are no specific tasks which are the responsibility of the client. Tasks requiring input from the client are identified as 'seeking information'.

Modelling technique

A variety of techniques exist for modelling data flow (Marca and McGowan, 1988; Martin and McClure, 1985). This research used data flow diagrams (DFDs) to model the design tasks and information exchange between them. The DFD methodology was selected because of its simplicity of use and the fact that the components can be translated to the relevant elements in the design process. The components of DFDs and our interpretation in the design context are shown in Figure 1. The processes represent design tasks, the data flows information exchange and the data stores standards, specifications or design files. Data sources or sinks are used to represent external entities or organizations such as the client, the contractors or local authorities. Further justification of the choice of DFDs over other techniques is given elsewhere (Gharib, 1991; Austin *et al.*, 1996b; Hassan, 1996).

Data flow diagrams are drawn in a hierarchical form. The top level, known as the 'context diagram' simply states the overall process. The context diagram was subdivided and the processes further decomposed until the decomposition identified the tasks that produced specific information requirements. In DFDs these bottom level tasks are known as 'functional primitive tasks' (FPTs). The level of detail within the FPTs was determined by the researcher in consultation with the industry representatives. No predetermined level of detail exists. FPTs represent specific tasks which the designer must complete for either the conceptual design report or the scheme design report to be completed. Although they represent design output they may not be separate design deliverables, i.e. calculations, drawings, sketches, etc. In our model, examples of functional primitive tasks include: estimate superstructure costs; calculate the approximate size of structural members; and decide finishes and materials.

Element	Software development description	Design process modelling description
Data or info. flow →	A connection between processes, etc., representing an input and/or an output	Design information flow
Process ○	Individual functions that a system carries out. They transform an input into an output	Individual design tasks, e.g. calculation, drawing, specifying
Data store	A collection of information that must be remembered for a period of time	Drawings, sketches, calculation files, reports, documents, specifications, computer files, etc.
Source/sink □	External entities with which the system communicates	Any external data source, e.g. client, local authority

Figure 1 Components of a data flow diagram for design

The hierarchy and structure of the model are shown in Figure 2. The model comprises six levels of detail from the context diagram (level 0). The model is divided into two main sections, one for concept design and the other for scheme design. It was found inappropriate to produce two separate models to cover these two stages of design, as invariably there was an overlap in the information requirements at the two stages.

Examples from several levels of the model are shown in Figures 3–7. Figure 3 (level 1) illustrates how the main model is divided into two main subsections, concept design and scheme design. Figure 4 (level 2, concept design) shows the main processes: building concept; site investigation; site planning; drainage concept design, and production of the concept design report. All output focuses on this main deliverable. Figure 5 (level 3) shows the building concept design divided into the three main processes: architectural concept design; the structural concept design; and services concept design. Figure 6 (level 4) expands the structural concept design into its three main components, foundations, superstructure, and floor slab. The superstructure design is then expanded in Figure 7 (level 5), showing the detail at the lowest level of the model. Here all the processes shown are functional primitive tasks. In total the model has 50 functional primitive tasks and 423 information flows. (For reasons of clarity not all of the functional primitive tasks have been shown within these figures).

A computer aided software engineering (CASE) tool was used to draw and amend the DFDs. In our research the CASE tool was used continually to draw the data flow diagrams, identify the components, and analyse and amend the model. Various reports were then produced by the CASE tool to help verify the model, including lists of all the model components (processes, information flows, data stores and data sources or sinks), the breakdown of the data flows into data elements, and the process inputs and outputs.

Further details on the use of data flow diagrams for systems analysis may be found in Demarco (1978), Ward and Mellor (1986). The use of data flow diagrams for construction research is also described by Pollard and Plume (1993) and Fisher and Lin (1992).

Application of the conceptual and schematic design data flow model

Using the model on its own

The design managers interviewed confirmed the generic conceptual and schematic design data flow model to be a useful monitoring tool to ensure the

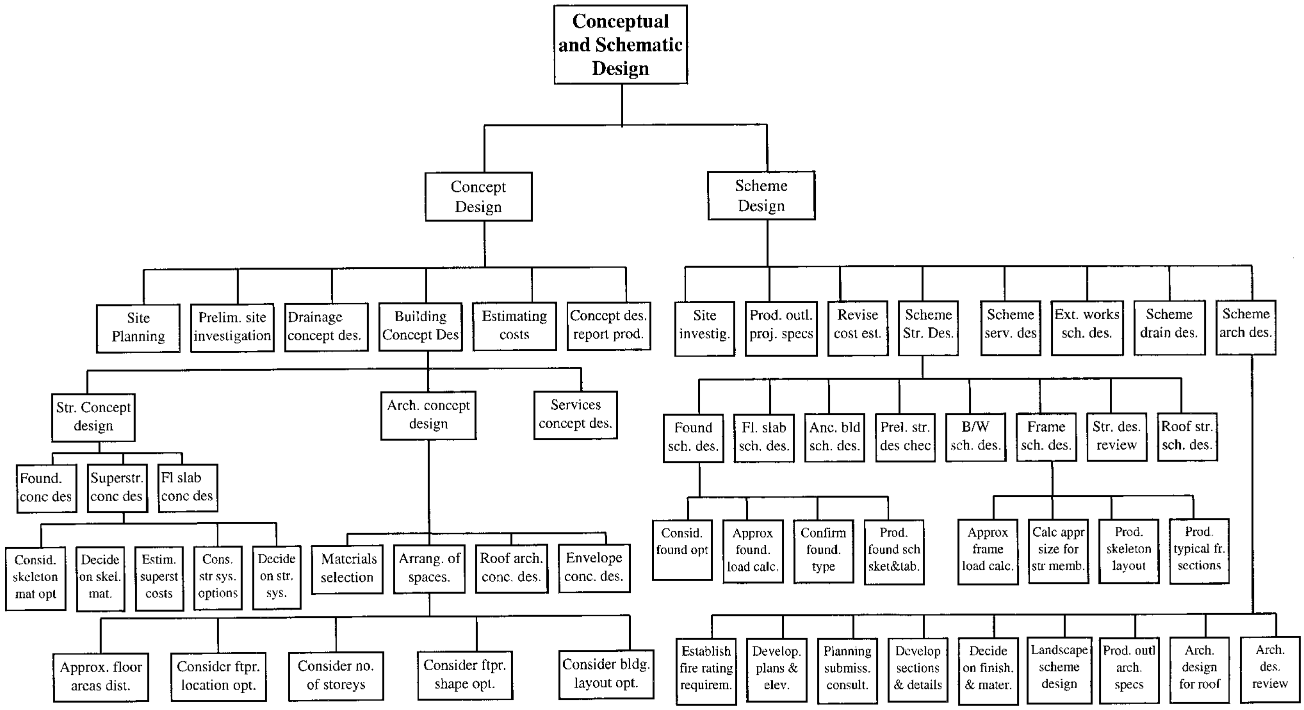

Figure 2 Structure of the generic data flow model for the conceptual and schematic design stages

completeness of information requirements for each design task. It provides a useful map of the overall process. Some design staff interviewed were content to use the data flow diagrams as an *aide memoire* in their normal form. Others stated a preference for the information within the model to be presented in alternative forms, e.g. checklists or as a matrix of responsibilities. Although the model was validated as a 'generic' model, it was accepted that on each project there would need to be an early review of the model to check that all the processes were relevant and the terminology was appropriate for the parties concerned. This was identified as a positive aspect of the model in that it helped the project team focus on the processes involved in the project from the earliest stages. The generic data flow model was found to provide immediate benefits to design managers. However, these can be enhanced greatly by the use of the model as a primary data source for other tools and techniques.

Application to analysis by the design structure matrix

Existing tools and techniques used for project planning purposes such as bar charts and network analysis do not accommodate iterative tasks. The DFDs within the conceptual and schematic design model do not on their own identify loops of iterative design tasks clearly. One method of doing this is to apply the partitioning techniques of the design structure matrix (DSM), developed originally by Steward (1981). This method is well suited to analysing information flows in design in order to identify an optimum sequence of tasks and the clusters of interdependent design activities. In the matrix, design tasks are organized first in any order as matrix rows and columns. Any dependence between tasks is identified by a mark in the relevant cell (Figure 8). If the mark exists under the diagonal of the matrix then the task provides input to a subsequent task. If the mark exists above the diagonal this indicates that the task provides input to an earlier task; such feedback dependence may be due to the poor ordering of the task or an unavoidable iteration in the logic of the design process.

By using partitioning algorithms, the tasks within the matrix can be reorganized to identify the optimum sequence of consecutive and iterative tasks, the latter clearly identifiable as blocks of tasks with marks above the diagonal (Figure 9.) The DSM can be used to: identify interdependent design tasks; optimize the order of design tasks; identify natural groupings of tasks; identify important interfaces between groupings of tasks; and analyse and explain the effects of changing the order of design tasks. (Austin *et al.*, 1995, 1996b).

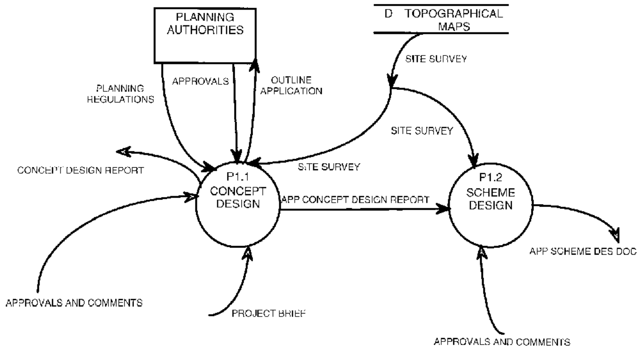

Figure 3 The conceptual and schematic data flow model: level 1, concept and scheme design

Although this can take account of only foreseeable dependence, the authors believe that the use of DSM focuses attention on the closely coupled blocks of tasks that require careful management, and as such reduces the likelihood of any lack of information disrupting the design work.

Simulating the design process

The generic data flow model and the design structure matrix provide the design manager with tools to analyse the design process and assess the impact of design changes. However, these techniques do not permit an assessment of the impact of events such as missing information, commencing a design task at an early time based on assumed information, and the other design management problems previously identified. As they stand, neither technique includes the allocation of resources or durations to each design task to produce a design schedule and assessment of resource utilization for the whole design process. This may be achieved by simulation.

The objective of developing a simulation model was to transform the generic data flow models from a static state to a dynamic state. After investigating the options for simulating the design process, a three-phase (see Tocher, 1963; Pidd, 1992) discrete event simulation approach was selected as the most appropriate simulation environment. Discrete event simulation allows

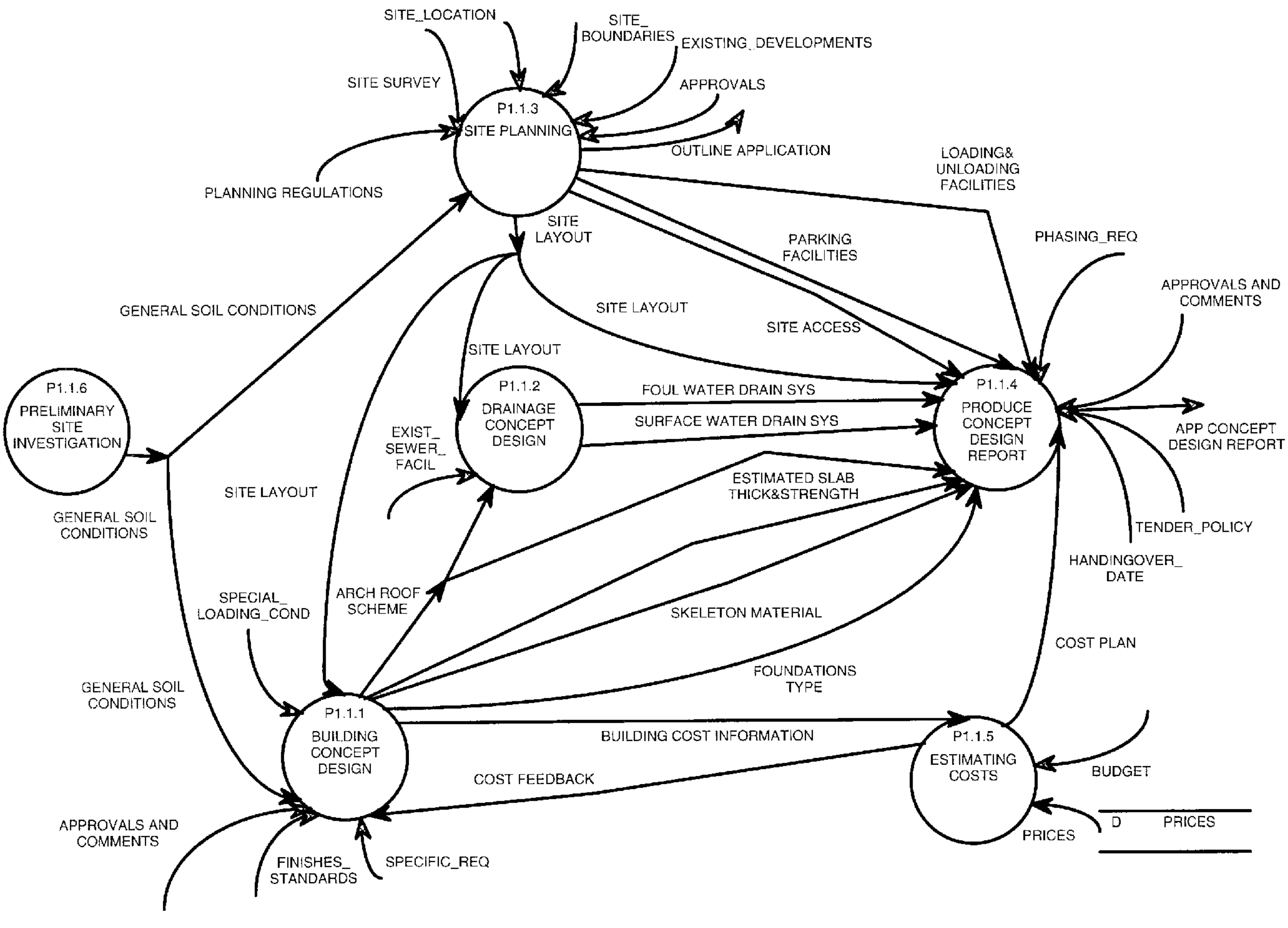

Figure 4 The conceptual and schematic data flow model: level 2, concept design

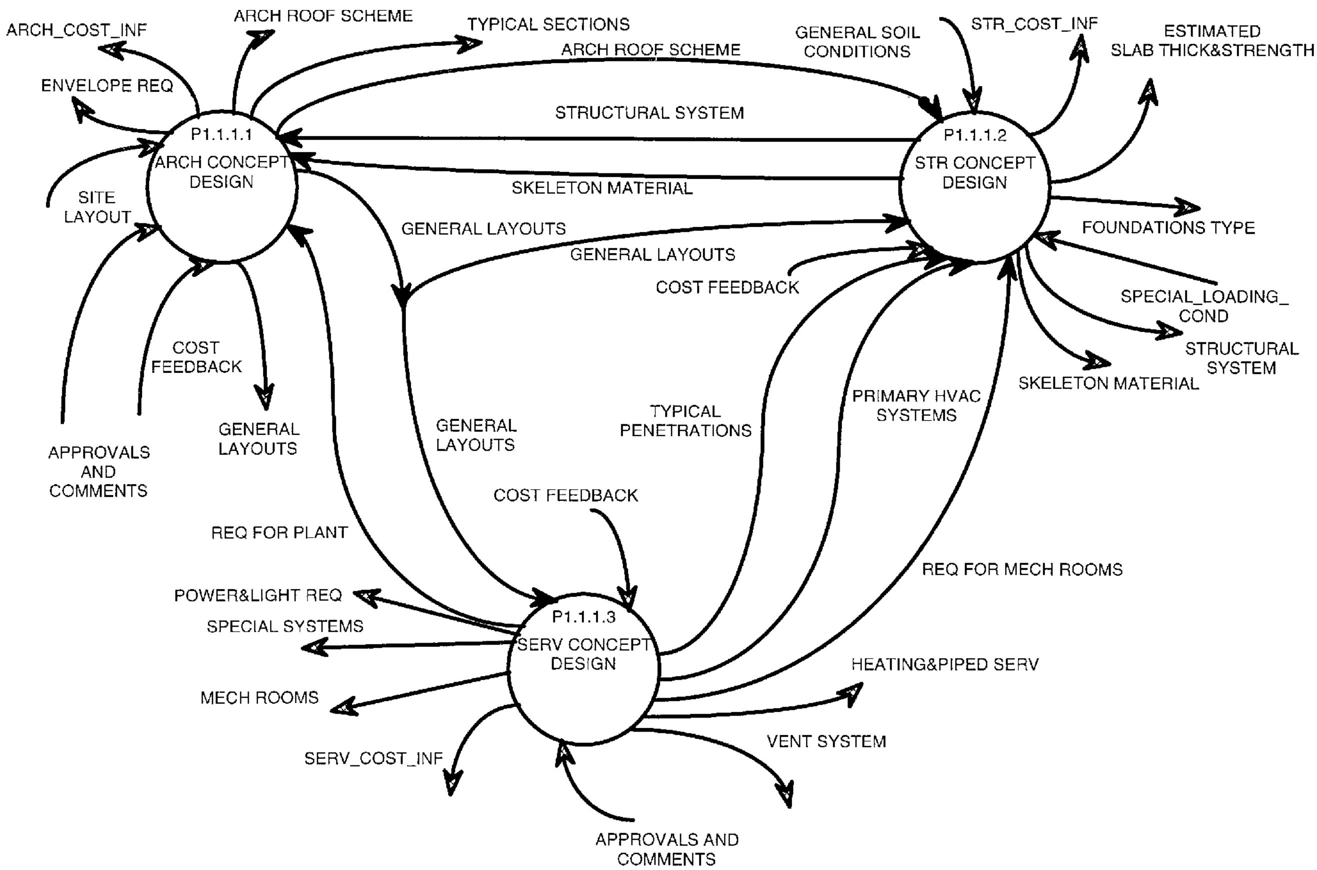

Figure 5 The conceptual and schematic data flow model: abstract from level 3, the three processes of building concept design

the user to interact with the model and to observe instantaneously the changes that occur in the model as the simulation clock advances, and typical events involved in this approach are well suited to representing design activities. The simulation software chosen provided flexibility in the modelling, with the possibility of incorporating conditional rules to execute the required actions when running the model. A more detailed discussion of the choice of technique and operation of the software is given elsewhere (Baldwin *et al.*, 1995, 1998; Hassan, 1996).

The relationship between the data flow model, the design structure matrix and the simulation model is shown in Figure 10. The data within the simulation model include the functional primitive tasks from the data flow model plus additional information such as task durations, resource requirements, data identifying the nature of the design tasks (e.g. iterative or non-iterative) and the information links between them. For each link specific attributes are identified, representing the information related events that have been identified prior to the start of the simulation. These data are stored in tables which are combined when the simulation is run. The tables also make provision for information that will be generated as the simulation proceeds, e.g. the start and finish times of every task, and the status of every task: ready to start; on going; completed first iteration; and completed. The user has the choice to run the model in either deterministic or stochastic mode (the latter by sampling from a normal distribution).

The results of the simulation displayed to the user include: a bar chart showing the start and end of every task and every iteration; icons showing the change of state of every task and resource as the simulation clock advances; and a resource histogram showing the levels of each resource (designer, draftsmen, etc.) required. These results allow the design manager both to track the status of the design tasks and resources as the simulation progresses and also to obtain final schedules which may be used to monitor progress and control resources.

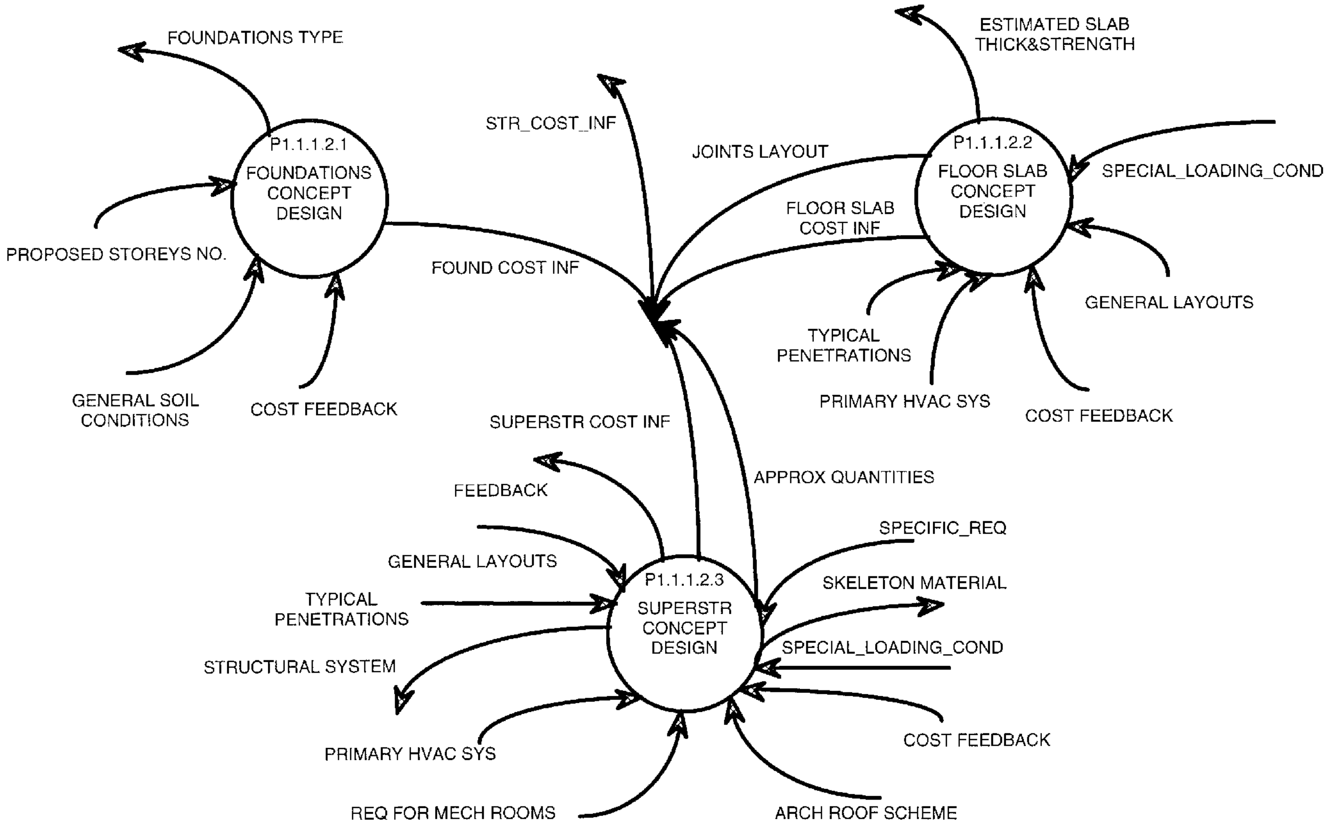

Figure 6 The conceptual and schematic data flow model: level 4, structural concept design

Industry feedback on the data flow modelling techniques

Throughout the research period close contact was maintained with architects and design engineers to gain feedback on the generic model and the tools and techniques developed. This feedback is reviewed under three sub-headings describing the important features (from the viewpoint of modelling) of conceptual and schematic design, the data flow model, and the tools and techniques developed.

Features of the conceptual and schematic stages of design

Important features/characteristics of the conceptual and schematic stages of design identified during the production of the model include the following.

(i) The model for the conceptual and schematic stages of design is independent of the procurement strategy. It shows the information requirements to complete design tasks not when these tasks are completed and by whom.

(ii) The schematic design stage is more difficult to manage than the detailed design stage, from the viewpoint of change. Changes at the schematic design stage tend to be more frequent and have a greater overall impact on the design than those at the detailed design stage.

(iii) There is no distinct pattern with respect to the difficult design tasks or the difficult sources of information. These vary from project to project.

(iv) The difficulty in obtaining information for tasks varied.

(v) The interviews identified all technical design information as important. Information such as the approved programme and approved cost plan were often seen as less important.

(vi) External information sources (e.g. different authorities, insurers, etc.) presented difficulties because of the time taken by them to take decisions or provide approvals. There was frequently a difficulty in the interpretation of regulations.

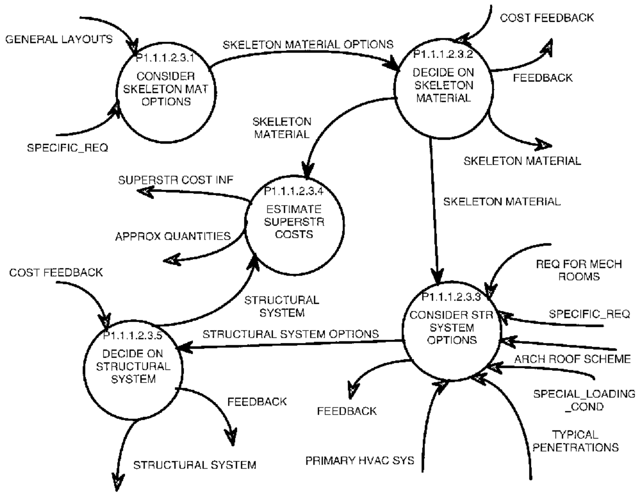

Figure 7 The conceptual and schematic data flow model: level 5, the breakdown of superstructure concept design

Such information sources often were the cause of redesign work.

(vii) There is no formal way to judge the quality of information exchanged. The measure of information quality varies according to the sender and the recipient of the information. Missing information or information of insufficient quality from the recipients point of view is normally supplemented by assumptions on the part of the recipient.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
A	■												X			X
B	X	■			X								X			
C	X		■									X				
D			X	■											X	
E				X	■							X			X	
F						■										
G						X	■	X						X		
H								■					X			X
I								X	■		X					
J						X	X		X	■				X		
K						X		X	X		■					
L											X	■				
M								X				X	■			X
N											X	X		■		
O											X	X		X	■	
P								X								■

Figure 8 Example of a matrix showing task relationships before partitioning

	F	H	I	K	L	M	P	N	O	G	J	A	C	D	E	B
F	■															
H		■				X	X									
I		X	■	X												
K	X	X	X	■												
L				X	■											
M		X			X	■	X									
P		X					■									
N				X	X			■								
O				X	X			X	■							
G	X	X						X		■						
J	X		X					X		X	■					
A						X	X					■				
C					X							X	■			
D									X				X	■		
E					X				X					X	■	
B							X					X			X	■

Figure 9 Example of a partitioned matrix showing coupled tasks/loops

The data flow model

The generic data flow model was the subject of numerous review meetings. These meetings resulted in refinements and suggestions which were incorporated into the model. The model also was validated against the actual design process during a case study of a major building project. The data collected included notes and observations recorded when 'shadowing' the design meetings. The information exchanged was recorded and then categorized within different headings and allocated to at least one of the information flows on the model. This confirmed that the model represented the design process subject to minor adjustments due to this specific nature of each project.

The generic data flow model was developed through several iterations. When validating the model, changes to initial versions of the model required amendments to some 30% of the information flows and some 10% of the tasks. This level of amendment quickly reduced to some 15% of the information flows and some 5% of the tasks. When using the generic model on a new project some changes to the model are inevitable to ensure that the model fully represents the individual project. This initial review of the model is seen as beneficial to the overall design process in that it requires the design manager consciously to consider all the tasks and information flows that may be required. Feedback from industry showed such a review to be beneficial and the levels of changes required were not considered onerous. Most of these changes were additions to the model for the clarification of project specific issues.

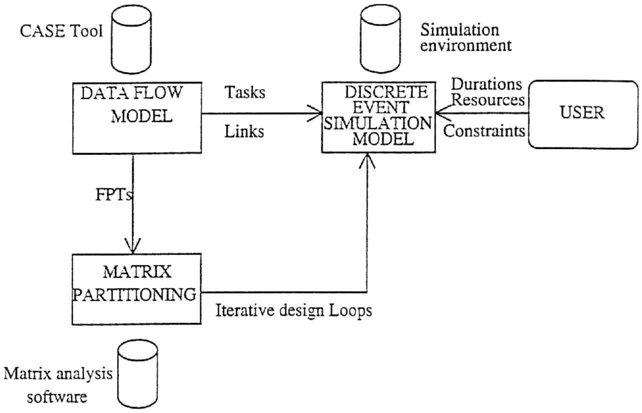

Figure 10 Relationship between the DFD model; the DSM model and the simulation model

A few tasks and information requirements were regarded by some interviewees as part of later stages of design. This is partly due to the natural overlap between the different stages of design and partly due to the lack of consensus among researchers and professionals in the construction industry as to the tasks that comprise each stage of design. However, to maintain the generic nature of the model, it was decided to retain these elements so that they may be used at the discretion of different user organizations. The feedback from industry highlighted the need for a better understanding of the conceptual and schematic stages of design and confirmed the contribution that this type of research provides to industry.

The tools and techniques developed

The industry representatives reviewed the DSM and simulation tools with interest and confirmed the technical and operational feasibility of using such tools to model the conceptual and schematic design phases. No economic evaluation or economic feasibility study was undertaken.

The DSM showed clearly the iterative tasks and was particularly useful in examining the impact of changes in task order due to client changes. Also of interest were the interfaces between groups of iterative tasks. These interfaces highlighted the information that needed to be provided before another part of the design work could begin. They focused design managers attention on the points in the design process where 'fixity' was essential to avoid design changes and abortive work.

The simulation model has been validated at a preliminary level through demonstrations to industry professionals using sample data in scenarios designed to replicate real situations identified in the earlier interviews. These included assessing the impact of: missing information; assuming information; the phased release of information; different levels of information quality; the gatekeeping of information; the impact of uncertainties; and the problems of resource management. The scenarios were explained and the industry representatives asked to rate the importance of the events within the conceptual and schematic stages of design together with the suitability of the tools to provide the solution. The results are shown in Table 2, which shows the relative importance of the events identified and confirms the suitability of the tools produced to analyse the problems. In all the scenarios demonstrated, the simulation was thought to be well suited to assisting the design manager in examining, scheduling and resolving issues, and identifying the effects of specific events.

However, it was agreed that there are no substantial benefits from running the simulation model solely to produce design schedules only for the conceptual design stage, because at this stage of the design process architects usually 'think' of more than one task simul-

Table 2 Feedback from industry representatives

Problem	Importance at conceptual and schematic design stage (scale 1–10)	Importance at detailed design stage (scale 1–10)	Suitability of the tools to provide a solution (scale 1–100)
Assessing the impact of missing information	7	8	76
Assessing the impact of assuming information	6	7	77
Assessing the impact of the phased release of information	6	8	75
Assessing the impact of different levels of information quality	4	7	60
Assessing the impact of gatekeeping of information	7	7	77
Assessing the impact of uncertainties	7	7	73
Assessing the impact of resource management	8	9	75

taneously. This aspect is very difficult to simulate, and allocating realistic durations to these tasks is problematical. At the conceptual design stage, a significant amount of time is spent 'thinking' around the design problem. This may vary according to the designer's experience and background and according to the project's particular circumstances. There is often a substantial amount of time spent waiting for the client to make decisions or provide information, which in turn depends on the type of client and/or the type of project; hence simulation would give unrealistic results. All the resources involved at this stage are small and hence there are no substantial benefits from simulating resources engagement or utilization. As the design progresses simulation offers real benefits to the design manager. Problems such as changes in design information, missing design information, gatekeeping of design information and variations in the quality of information exchanged during the design process become more readily apparent as the design progresses. All such problems may be investigated and evaluated using simulation. However, it is concluded that only in the schematic and detailed phases of design are techniques such as simulation truly feasible within a design environment.

Conclusions

The importance of improved design management is now widely recognized. The survey and interviews undertaken within this research confirmed that the management of the conceptual and schematic stages of design are particularly difficult. These phases represent the 'front end' of the detailed design stage, and problems in managing the early stages will affect the whole design process. Decisions made at this early stage of design also have a major influence on the overall project cost. Difficulties in managing information flow and difficulties in planning and scheduling design work are particular problems for the design manager.

It is only by a better understanding of the flow of information among project participants that the management of design may be improved. There is considerable research focus at present on process models of the design and construction process. The research described in this paper complements such studies. We have argued that existing models of the design process are inadequate if we are to obtain a detailed understanding of information related events. The generic conceptual and schematic data flow model produced as part of this research programme provides design managers with a basis for monitoring the production of design information. When data from the model are used with other tools and techniques a more detailed analysis of problems such as missing information, the phased release of information, uncertainty and other scenarios of information exchange may be assessed. However, the potential of techniques such as discrete event simulation to model the building design process, particularly the conceptual design stage, is restricted because of the inherent nature of this stage of the design process.

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References

Addis, W. (1990) *Structural Engineering*, Ellis Horwood, Chichester.

Ahuja, H.N. (1984) *Project Management Techniques in Planning and Controlling Construction Projects*, Wiley, Chichester.

Austin, S.A., Baldwin, A.N. and Newton, A.J. (1994) Improved building design programming by manipulating the flow of design information, *Construction Management and Economics*, **12**(5), 445–55.

Austin, S.A., Baldwin, A.N. and Newton, A.J. (1996a). A data flow model to plan and manage the building design process, *Journal of Engineering Design*, **7**(1), 3–25.

Austin, S.A., Baldwin, A.N., Hassan, T.M. and Newton, A.J. (1996b) Techniques for the management of information flow in building design, in *Proceedings of the International Conference on Information Technology in Civil and Structural Engineering Design (ITCSED '96), Strathclyde, UK, August 1996*, pp. 119–23.

Austin, S.A., Baldwin, A.N., Thorpe, A. and Hassan, T.M. (1995) Simulating the construction design process by discrete event simulation, in *Proceedings of the International Conference on Engineering Design, ICED 95, Prague, August*, pp. 762–72.

Baldwin, A.N., Austin, S.A., Hassan, T.M. and Thorpe, A. (1998) Planning building design by simulating information flow, *Automation in Construction*, in press.

Baldwin, A.N., Austin, S.A., Thorpe, A. and Hassan, T.M. (1995) Simulating quality within the design process, in *Proceedings of the American Society of Civil Engineers (ASCE) Second Congress on Computing in Civil Engineering, Atlanta, Georgia, June*, pp. 1475–82.

Bennett, J., Flanagan, R., Lansley, P., Gray, C. and Atkin, B. (1988) *Building Britain 2001*, Centre for Strategic Studies in Construction, Reading.

BSI (1994) BS7000, Part 4, Draft, *Guide to Managing Design in Construction*, BSI, London.

Cornick, T. (1991) *Quality Management for Building Design*, Butterworth-Heinemann, London.

Cross, N. (1984) *Developments in Design Methodology*, Wiley, Chichester.

Cross, N. (1991) *Engineering Design Methods*, Wiley, Chichester.

Demarco, T. (1978) *Structured Analysis and System Specification*, Yourdon Press (Prentice-Hall), Englewood Cliffs, NJ.

Dias, W.P.S. and Blockley, D.I. (1994) The integration of product and process models for design, *Design Studies*, **15**(4), 417–32.

Fisher, N. (1990) The use of structured data analysis as a construction management research tool: the technique, *Construction Management and Economics*, **8**(4), 341–63.

Fisher, N. and Lin, S. (1992) *Information Management in a Contractor – A Model of the Flow of Project Data*, Thomas Telford, London.

French, M.J. (1985) *Conceptual Design for Engineers*, Design Council, London.

Frost, R. (1992) A converging model of the design process analysis and creativity, the ingredients of synthesis, *Journal of Engineering Design*, **3**(2), 117–26.

Gharib, K.M. (1991) Modelling information flow within a design and build organization, M.Sc. project, Loughborough University.

Gray, C., Hughes, W. and Bennett, J. (1994) *The Successful Management of Design*, The University of Reading.

Hassan, T.M. (1996) Simulating Information Flow to Assist Building Design Management, Ph.D. thesis, Loughborough University.

Marca, D. and McGowan, C. (1988) *SADT – Structure Analysis and Design Techniques*, McGraw-Hill, New York.

Martin, J. and McClure, C. (1985) *Structured Techniques for Computing*, Prentice-Hall, Englewood Cliffs, NJ.

McGee, P.(1992) Internal Confidential Report for AMEC Design and Management.

Ndekugri, I. and McCaffer, R. (1988) Management information flow in construction companies, *Construction Management and Economics*, **6**(4), 273–94.

NEDC (1987) *Achieving Quality on Building Sites*, Building and Economic Development Committee (NEDO), London.

Newton, A.J. (1995) The Planning and Management of Detailed Building Design, Ph.D. thesis, Loughborough University.

Pahl, G. and Beitz, W. (1988) *Engineering Design: A Systematic Approach*, Design Council, London.

Pidd, M. (1992) *Computer Simulation in Management Science*, 3rd Edn. Wiley, Chichester.

Pollard, A. and Plume, J. (1993) Can architectural design learn from software engineering?, in *Proceedings of the Third International Building Performance Simulation Association Conference, Adelaide, Australia, August*, pp. 327–33.

Powell, J. and Newland, P. (1993) Construction Information: An Integrating Interface to Data, SERC N&N Workshop, University of Salford, UK.

Price, G.M. (1995) The Management of Building Services Engineering Design, M.Sc. project, Loughborough University.

RIBA (1973) *Plan of Work for Design Team Operation*, RIBA Publications, Royal Institute of British Architects, London.

Steward, D. (1981) The design structure system: a method for managing the design of complex systems, *IEEE Transactions on Engineering Management*, **EM-28**(3), 71–4.

Tocher, K.D. (1963) *The Art of Simulation*, English Universities Press, London.

Topalian, A. (1979) *The Management of Design Projects*, Associated Business Press, London.

Ward, P. and Mellor, S. (1985) *Structured Development for Real-Time Systems*, Prentice-Hall, Englewood Cliffs, NJ.