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Application
of
Design for Manufacture Principles
to
Building Design and Construction

Stephen John Fox

A thesis submitted in partial fulfilment of the requirements of
Sheffield Hallam University
for the degree of Doctor of Philosophy

March 2001

Application of Design for Manufacture Principles
to Building Design and Construction

STEPHEN JOHN FOX

ABSTRACT

The aim of this thesis is to answer the two research questions: how can design for manufacture be *applied* during building component design and building design?; and how can the application of design for manufacture be *successful* in improving the productivity and quality of building component production and building construction?

These two questions emerged during exploratory research focused on the use of design to improve construction industry productivity and quality. Subsequent review of manufacturing literature revealed that the two key principles of design for manufacture are standard production design improvement rules and standard production design evaluation metrics. Review of construction literature, and a survey involving over one hundred and fifty industry practitioners, revealed that, whilst rules and metrics for building components and buildings do not currently exist, there are no fundamental reasons why they could not be developed and applied successfully. These findings led to the generation of the research hypothesis: design for manufacture principles can be applied successfully to building components and buildings.

The research hypothesis was tested by two interventions, action research within a private business which manufactures and installs building components, and a case study with a multi-national company which designs and constructs buildings. These interventions resulted in significant business benefits. Further, they confirmed that it is both technically feasible and economically viable to apply rules and metrics to building component design and building design, and that doing so can improve the productivity and quality of building component production and building construction. Following analysis of research findings, strategic plans were developed for the successful application of rules and metrics. These were validated through interviews with senior construction industry practitioners.

Contributions to knowledge include the strategic plans for successful application of rules and metrics. These cover the full range of organisations working in the construction industry and, together with the detailed descriptions of the interventions, offer practical guidance for industry practitioners seeking to improve productivity and quality. The research also makes a contribution in the area of research methodology. It has shown that threats to research validity in the construction industry can be counteracted by applying a quasi-experimental perspective to action research interventions and case studies.

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Abbreviations

BoMs	Bills of Materials
CIOB	Chartered Institute of Building
CIRIA	Construction Research and Information Association
CSSC	Centre for Strategic Studies in Construction
DETR	Department of the Environment, Transport and the Regions
DFM	Design for Manufacture
NEDO	National Economic Development Office
RCF	Reading Construction Forum
RICS	Royal Institute of Chartered Surveyors
SME	Small- to Medium-sized Enterprise

List of Publications

Fox, S., Staniforth, I. and Cockerham, G. (1999) World Class Craft. *Manufacturing Engineer*, Manufacturing Division of The Institution of Electrical Engineers, **78** (4), 145 -148

Fox, S., and Cockerham, G. (2000) Designing for orders. *Manufacturing Engineer*, Manufacturing Division of The Institution of Electrical Engineers, **79** (2), 63 - 66.

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Fox, S. and Cockerham, G. (2000) Matching design and production. *the architects' journal*, emap business publications, **211** (9), 50 - 51.

Fox, S. and Cockerham, G. (2000) Designs on construction. *the architects' journal*, emap business publications, **212** (19), 44.

Fox, S., Marsh, L. and Cockerham, G. (2001) Design for manufacture: a strategy for application to buildings. *Construction Management and Economics*,

As indicated by the editor's letter in Appendix L, this paper was accepted in January 2001.

Acknowledgements

The research reported in this thesis was made possible by the participation of nearly two hundred industry practitioners. From company directors to site operatives, all of these people have demanding jobs to do, and I am very grateful for the time which they made available to me, whether this was a few minutes answering a questionnaire or a few months contributing to a case study. In addition, the dissemination of my research, has involved input from journal referees, editors and administrators. Their comments and suggestions have been very instructive and much appreciated.

Above all, I wish to acknowledge the advice and support provided by my Director of Studies, Professor Graham Cockerham, his secretary, Mrs Jean Grove (School of Engineering, Sheffield Hallam University) and my Supervisor, Dr Laurence Marsh (Department of Construction Management and Engineering, University of Reading). Throughout the research, their counsel has been invaluable.

Preface

My interest in improving the productivity and quality of building construction began during my apprenticeship as a carpenter and joiner. Working on site, I became aware that my output could have been increased if more attention had been paid to production during design. For example, as an apprentice, I would often have to cut down the backs of door frames so they would fit into wall openings. Then, I would have to plane down doors so they would fit into those frames. This work was only necessary because installation tolerances had not been allowed for when wall openings and door frames had been dimensioned.

The company with which I served my apprenticeship was a small provincial building contractor and developer. In the case of this example, the company bought in the doors, manufactured the frames, and constructed the wall openings. The company took pride in always manufacturing components, such as door frames, exactly as they had been designed. They would not seek to modify designs, with the architect's consent, for ease of production. Similarly, the company would always try to construct buildings exactly as they had been designed. Although the company would criticise architects' designs, they would not provide architects with the information which would have made their designs simpler to construct.

My experiences as an apprentice were often repeated when I worked as a carpenter and joiner for specialist contractors in London. However, these companies would sometimes try to modify designs to eliminate major production problems. To return to the example of doors and frames, some did manufacture frames to suit door sizes and construct wall openings to suit frame sizes. When this happened I was able to fit doors and frames far more quickly. Also, without any more diligence on my part, the quality of my work improved because, with far less cutting to do, there were far fewer opportunities to make mistakes. It was at this time, that I began to recognise that productivity and quality can be improved simultaneously. Prior to then, I had accepted with the conventional trade wisdom that work could be "slow and right or fast and rough".

However, it was only when I became an operational manager for a principal contractor that I realised how much time is required to modify architects' designs and receive their approval prior to production. This process can often delay the start of both building component manufacture (such as joinery) and building construction work (such as carpentry). When production is delayed, it is often necessary to work overtime which, in turn, can have a negative affect on productivity and quality. It is reported in Chapter 2 that these problems are widespread and longstanding. However, during my career I have not met any building designers or building component designers, who use formal design methods to improve productivity and quality. Also, I have never come across any production personnel who encourage them to do so.

Further, when studying the syllabuses of the City & Guilds Institute and the Chartered Institute of Building, I did not encounter any reference to formal design methods. I only learnt that these exist when I became a delegate on the Integrated Graduate Development Scheme (IGDS).

Subsequently, for my IGDS M.Sc. thesis, I developed and tested a set of building component evaluation tables.These tables do not address all stages of production. They provide a method of evaluating "installability". Two samples are shown in Figures P.1 and P.2 below. The tables are only applicable to standard manufactured building components which are made for stock, such as external doors and roof windows. The tables are not intended for evaluating processed building components, such as concrete and plaster, which are equally essential to building construction. Also, they are not applicable to bespoke manufactured components made for one-off orders. Nor are they applicable to entire buildings.

The tables were used to evaluate ten alternative designs for one type of window component by several employees of the same company. They enabled a wide range of factors to be considered systematically by people who worked in different departments and had different perspectives. This experience provided me with a practical insight into the benefits of design methodologies. The component design which received the highest evaluation score has subsequently been developed and introduced by the company.

Figure P.1: Sample of work contained in M.Sc. Thesis.

INSTALLATION EVALUATION SUMMARY FORM FOR STANDARD MANUFACTURED BUILDING COMPONENTS.©

COMPONENT NAME: .... COMPONENT REFERENCE .... SUMMARY PREPARED BY .... DATE ..../......../........

CATEGORIES	FACTORS	NOTES	OPERATIONAL STAGE COST SIGNIFICANCE SCORES					SUB-TOTALS	
			BUY (0 - 5)	MANUFAC-TURE (0 - 10)	FABRI-CATE (0 - 20)	INSTALL (0 - 60)	INVOICE (0 - 5)	FACTOR (0 - 100)	CATEGORY (0 - 400)
NEED FOR PROTECTION	1. DURING STORAGE & HANDLING								
	2. DURING FABRICATION								
	3. DURING INSTALLATION								
	4. AFTER HANDOVER								
THEFT (ALTERNATIVE USE VALUE)	1. PARTS								
	2. COMPLETED COMPONENT								
	3. INSTALLED COMPONENT								
	4. PLANT & EQUIPMENT								
INSURANCE ISSUES	1. FIRE								
	2. SAFETY								
	3. CERTIFICATION(S)								
	4. WARRANTIES								
DETERIORATION OF INSTALLED COMPONENT	1. ACCIDENT / VANDALISM								
	2. POLLUTION								
	3. CONSTRUCTION FORM								
	4. WEAR AND TEAR								

Figure P.2: Sample of work contained in M.Sc. Thesis.

THEFT (ALTERNATIVE USE VALUE) EVALUATION FACTORS

COMPONENT NAME: .... COMPONENT REFERENCE .... EVALUATION PREPARED BY .... DATE ....../....../......

CATEGORY	FACTORS	NOTES	OPERATIONAL STAGE COST SIGNIFICANCE SCORES					TOTALS	
			BUY (0 - 5)	MANUFAC-TURE (0 - 10)	FABRI-CATE (0 - 20)	INSTALL (0 - 60)	INVOICE (0 - 5)	FACTOR (0 - 100)	CATEGORY (0 - 400)
THEFT (ALTERNATIVE USE VALUE)	1. PARTS								
	2. COMPLETED PRODUCT								
	3. INSTALLED PRODUCT								
	4. PLANT & EQUIPMENT								

Generally. In a factory environment control of components is more straightforward than on a building site where the movement of operatives and visitors cannot be easily directed, restricted, or observed. Also, the costs of theft on a building site are not limited to those of replacement, and increased insurance premiums. They can include repeated provision of temporary secure storage, expediting the delivery of replacements, expediting works delayed by the theft of parts/products and disruption to other works caused by this, delayed / part payment due the theft of installed products, contra-charges and set-off due to causing delay to the work of other trades, and loss of reputation.

1. Parts. Low scores can be assigned where no high value items (e.g. gold handles) or easily adapted items (e.g. timber braces) will be sent "loose" to site, and none are highly visible on the completed component.

2. Completed component. The nature of a component will often determine its resale value, and even if lower cost materials are used this is unlikely to be obvious to a thief. Consequently, low scores can be assigned where design addresses how to make the component easy to store securely and difficult to resell. This may involve consideration of packaging and labelling.

3. Installed component. As well as designing a component so it is difficult to steal (due to robust fixings etc.,) it must be made as clear as possible that it is difficult to, steal and use or, steal and resell. Low scores can be assigned where measures to achieve this have been identified.

4. Plant and equipment. These are often easier to, steal and use or, steal and sell than the component they are used to handle and fix. Ownership is an important issue. For example, a fork lift truck used for handling is likely to be owned by the customer and a hand drill by the operative: neither by the installer. Low scores can be assigned where the component has been designed for installation with the minimum amount of installer-owned plant and equipment

After successful completion of my M.Sc., I investigated the relative performances of the construction industry and the manufacturing industry during the past twenty years. Impressed by the often quite remarkable results achieved through the use of DFM methodologies in the manufacturing industry, I began to consider whether DFM methodologies could be successfully applied to buildings. It seemed to me that even if DFM could be only half as successful in the construction industry as it is in the manufacturing industry, the results would still be very significant. Thus, having resolved to take action, I sought guidance from my M.Sc. thesis supervisor, Professor Graham Cockerham, Deputy Director of Sheffield Hallam University's School of Engineering.

Subsequently, I carried out some exploratory discussions with building design, and building production, practitioners. All of these practitioners felt that the productivity and quality problems of the construction industry were not getting any better. Most interestingly, even though these practitioners worked for large organisations, none of them had heard of formal production design methodologies.

Having identified the need for this original contribution to knowledge, I then secured the commitment of companies to participate in research. This enabled me to register as a research degree student at Sheffield Hallam University with Professor Cockerham as my Director of Studies.

Industrial participation in my research was varied, but was led by two companies, one multi-national construction management organisation and one medium-sized building component manufacturer and installer. The multi-national carries out the management of building design and building construction. It employs architects, consulting engineers, quantity surveyors, project managers and construction managers. Throughout the thesis, this company is referred to by means of the pseudonym, “Contractor-X”. The medium-sized enterprise carries out the production design, manufacture and installation of bespoke components for a wide range of building types. Throughout the thesis, this company is referred to by means of the pseudonym, “Supplier-Y”. The names of both companies and all their personnel are withheld due to the sensitive nature of some of the details provided.

1.0 Introduction

1.1 Introduction

In this chapter, the background to the research is discussed. Further, the research hypothesis is stated and justified. In addition, an overview of the research methodology is provided, and an outline of the thesis is presented.

1.2 Background

It has long been recognised, in both the manufacturing industry (Peck, 1973) and the construction industry (Emerson, 1962), that productivity and quality can be improved by integrating production best practice into designs. In the manufacturing industry, this recognition has led to improvements in productivity and quality (Dean and Susman, 1989). However, in the construction industry, low productivity and poor quality continue to be widely reported (Barber *et al*, 2000).

Many product design engineers are able to integrate production best practice into designs because they have been provided with methodologies to help them do so. These proprietary methodologies have been developed largely by production experts, and comprise standard production design improvement rules and standard production design evaluation metrics.

The term used to describe these production design methodologies is, "design for manufacture" (DFM). Their use has resulted in many companies having fewer quality problems, and radically reduced production costs and times (Francis, 1994). For example, IBM have reported a cut in printer assembly time from thirty minutes to three minutes (Vonderembse and White, 1991). These improvements have been achieved whilst product specifications have been raised.

Throughout this thesis, the term DFM refers to proprietary DFM methodologies rather than the "philosophy of design for manufacture". There are two reasons for this. Firstly, as reported in detail in Chapter 4, the content of these methodologies is well-defined, and the results of their application have been quantified by third parties. As a consequence, survey research can define factors which are critical to their application and essential to their success. Further, experimental research can be undertaken with a DFM methodology as the independent variable and productivity and quality as the dependent variables. In contrast, the content and use of a philosophy are far harder to define. Indeed, a philosophy can be perceived differently by different people. Further, the benefits resulting from a philosophy's existence are very difficult to isolate, and almost impossible to quantify. Secondly, as reported in detail in Chapter 2, there has been a production design philosophy in existence for some twenty years in the construction industry. This production philosophy is widely known as buildability in the UK (Ferguson, 1989) and as constructability in the USA (Dunston and Williamson, 1999).

However, there is no equivalent to the proprietary DFM methodologies in the construction industry. In the construction industry, building designers have not been provided with equivalent methodologies, and the integration of production best practice into designs continues to rely on the varying experience of individuals (McGeorge and Palmer, 1997). Building designers are often held responsible for the shortcomings of this haphazard approach (Harding, 1999). Similarly, integrating production best practice into product designs, was a largely unachieved objective in the manufacturing industry before DFM was introduced. Now, by following DFM design improvement rules, design engineers are much better able to integrate production best practice into their product designs (Whitney, 1988). Further, design engineers no longer have to start from scratch and "reinvent the wheel" when they begin to design a product. Instead, by making reference to DFM design evaluation metrics, they can carry out quantified evaluations of alternative concepts, configurations and details throughout the design process. In addition, they are able to select from quantified comparisons of different materials, processes and components. The results of implementing DFM have often been quite remarkable. For example, some manufacturers have claimed production cost reductions of up to 50% (Ulrich and Eppinger, 1995).

The potential benefits of applying DFM to buildings have been recognised for some time (Anumba and Evbuomwan, 1997), and the Report of the Construction Industry Task Force (DETR, 1998) recommends that the construction industry develops an equivalent to DFM.

1.3 Research Hypothesis and Justification

Although the potential benefits of applying DFM to buildings are becoming more widely recognised (Cox *et al*, 1999), little research has been undertaken into the two questions stated below.

- How can DFM be *applied* during building component design and building design?
- How can DFM application be *successful* in improving the productivity and quality of building component production and building construction?

As described in subsequent chapters, the inductive research used to investigate these two fundamental questions resulted in the generation of the research hypothesis stated below.

DFM principles can be applied successfully to building components and buildings

Within the context of this hypothesis, the term, *DFM principles*, refers to the two key factors listed below.

- Standard production design improvement rules (**rules**).
- Standard production design evaluation metrics (**metrics**).

Also within the context of this hypothesis, the word, *buildings*, encompasses all types of space enclosures from small domestic dwellings to large commercial and public facilities such as factories, hospitals, hotels, offices, and stadia. *Building components* includes all levels from formless materials to discrete assemblies.

The inductive research reported in this thesis revealed that differences between the design process for buildings and the design process for manufactured goods would often prevent *application* of existing DFM methodologies. The research also revealed that opportunities for *successful* application would be limited due to differences between the production processes commonly used for buildings and the processes typically used to produce manufactured goods.

Analysis of the content of DFM methodologies resulted in the identification of rules and metrics as being DFM principles. The potential for successfully applying rules and metrics to different types of building components and buildings was assessed. During this process the hypothesis was generated: *DFM principles can be applied successfully to building components and buildings*.

The deductive research which followed addressed two major shortcomings of existing knowledge: how can DFM principles be *applied* during building component design and building design, and how can the application of DFM principles be *successful* in improving the productivity and quality of building component production and building construction.

As the proportion of construction productivity and quality problems attributable to design has remained at about fifty percentage for the past twenty years (BRE, 1981; Barber *et al*, 2000), this new contribution to knowledge will be of considerable value for the construction industry and its clients.

1.4 Research Objectives

The four objectives of the research work described in this thesis are stated below.

- To provide an analysis of factors critical to DFM application and essential to DFM success, and to identify where, if at all, these factors can be found in building design and production.

- To investigate how DFM principles can be applied successfully to building components.

- To investigate how DFM principles can be applied successfully to buildings.

- To develop and validate strategies for the successful application of DFM principles to all building components and buildings.

1.5 Research Methodology

The research comprised the following phases: definition of the two research questions; generation of the research hypothesis; testing of the research hypothesis; and development of the hypothesis into DFM strategies for the construction industry.

Figure 1.1 provides a chronology of the research work which was undertaken. The research began in July 1997 with exploratory literature survey and was completed in December 2000 with practitioner interviews to validate strategies for the successful application of DFM principles.

Figure 1.1: Research chronology

Months	Research stage	Research work
1 - 6	Exploratory work	*Initial literature review and unstructured interviews*
5 - 10	Research design	*Selection of appropriate research strategies*
10 - 33	Inductive research	*Further literature review and field survey*
12 - 39	Deductive research	*Action research intervention with Supplier-Y*
18 - 35		*Case study with Contractor-X*
38 - 42	Development	*Interviews to validate DFM strategies for Construction*

Research questions were defined after an initial literature review, and following several unstructured interviews with industry practitioners. The generation of the research hypothesis took place during analysis of findings from further literature review and a more extensive field survey with industry practitioners. Literature review focused on factors critical to DFM application and essential to DFM success. The field survey involved three sets of interviews, and a postal questionnaire. Hypothesis testing consisted of two interventions: action research within Supplier-Y, and a case study within Contractor-X. During this deductive research, multiple instruments were used to gather data from numerous sources. Development DFM strategies for the construction industry took place during analysis of research findings. The strategies were validated during interviews with industry practitioners.

There are many factors which are difficult to isolate and control in the fragmented and volatile environment of building design and building production. Consequently, particular emphasis was placed on defining threats to research validity during the design of research instruments. Factors which can reduce the trustworthiness of both quantitative and qualitative data were considered. Tactics to deal with these factors were made explicit before data collection began and adhered to throughout the research.

1.6 Thesis Outline

Figure 1.2 shows an outline of the thesis. Each of the chapters focuses on a particular aspect of the research. Together they provide record of the work carried out and the original contribution to knowledge which has been achieved.

Figure 1.2: Outline of the Thesis

Chapter	Research stage	Output
2	Exploratory work	*Research questions*
3	Research design	*Research methodology*
4	Inductive research	*Research hypothesis*
5	Deductive research	*Results of applying DFM principles to building components*
6		*Results of applying DFM principles to buildings*
7	Development	*DFM strategies for the construction industry*
8	Discussion	*Definition of research themes and impacts*
9	Conclusions	*Definition of research conclusions*

Chapter 1 - Introduction

This chapter acts as a foundation to the main body of the thesis. It outlines the relevance, purpose, value and structure of the research.

Chapter 2 - Literature Review and Exploratory Interviews

In this chapter, findings from the exploratory investigation are presented. The progressive review of the literature which was carried out is described, and findings from unstructured interviews with industry practitioners are reported. During the literature review, the following five themes emerged:

- continued low productivity and poor quality in the construction industry;
- improved productivity and quality in the manufacturing industry;
- lack of DFM application in the construction industry;
- characteristics of manufacturing design and construction design;
- the affect of design on productivity and quality.

As shown in Figure 1.2, the work which is described in Chapter 2 resulted in the definition of the two research questions:

- how can DFM be *applied* during building component design and building design?
- how can DFM application be *successful* in improving the productivity and quality of building component production and building construction?

Chapter 3 - Research Methodology

Chapter 3 describes the formulation of the research strategy, and the selection of research techniques to fulfill that strategy. The challenges of conducting good quality field research in the construction industry are discussed, and the tactics used in this research to address those challenges are defined.

Chapter 4 - Survey: DFM Application Issues and DFM Success Issues

In this chapter, the findings of further research comprising literature review and field survey are reported. This includes an overview of DFM in the manufacturing industry, and an analysis of issues affecting potential DFM application and DFM success in the construction industry. The field survey comprised two sets of interviews and one postal questionnaire supported by one set of follow-up interviews. Each set of interviews was carried out with a separate sample of fifteen practitioners, whilst a larger sample of two hundred and sixty-seven practitioners was used for the questionnaire. All of the field survey participants were directly employed by Contractor-X or worked with Contractor-X during building design and/or building construction. Participants were asked to respond on their experiences in the three years leading up to the field survey. The work reported in Chapter 4 led to the generation of the research hypothesis: *DFM principles can be applied successfully to building components and buildings*

Chapter 5 - Study I: Applying DFM principles to building components

Chapter 5 describes the action research intervention designed to determine how DFM principles can be successfully applied to building components. The intervention was conducted over a twenty-seven month period within Supplier-Y. This private company manufactures a variety of building components from a diverse range of materials. During the intervention, the author was employed by Supplier-Y in a position which involved the development of corporate strategy and the management of its execution. Prior to the intervention, the business did not have a formal design method to improve the productivity and quality of component manufacture and installation. Now, the business applies DFM principles during routine order processing. As a result, the business' productivity and quality have been improved whilst its financial turnover has risen.

Chapter 6 - Study II: Applying DFM principles to buildings

This chapter describes a case study designed to determine whether DFM principles can be successfully applied to buildings. The case study was conducted over a seventeen month period. It addressed the design and construction of a large healthcare facility. Participation was led by Contractor-X, but representatives from several other organisations were involved. These ranged from multi-nationals to small- to medium-sized enterprises. During the case study, standard production design improvement rules and standard production design evaluation metrics for construction were formulated and trialed. This resulted in the productivity and quality of construction being demonstrably improved.

Chapter 7 - Development: DFM Strategies for the Construction Industry

In this chapter, strategies for achieving successful application of DFM principles in the construction industry are proposed and explained. To inform assessment of these strategies, DFM development issues are discussed. These are categorised as:

- classification issues;
- formulation issues;
- application issues; and
- success issues.

Individual strategic plans are presented for specific types of construction organisations. These plans offer the construction industry practical guidance based on the inductive and deductive research carried out earlier. The strategic plans were presented to industry practitioners and their attitudes towards them are reported.

Chapter 8 - Discussion

In Chapter 8, the research focus is revisited and the major themes of the research are discussed. Also, the impacts of the research on Supplier-Y, Contractor-X, the construction industry, and the author are described.

Chapter 9 - Conclusions

In this final chapter, the research conclusions are stated, the originality and contribution to knowledge of the research are described, and recommendations for further research are provided.

1.7 Chapter Conclusion

This first chapter has laid the foundations for the thesis. The background to the research has been discussed. Then, the research questions, the research hypothesis, and the research objectives have been stated. Also, the chronology and content of the research methodology have been introduced. Further, an outline of the thesis has been provided.

2.0 Literature Review and Exploratory Interviews

2.1 Introduction

As described in the Preface, the research reported in this thesis began with an exploratory investigation focused on:

the use of design to improve construction industry productivity and quality.

In this chapter, findings from the exploratory investigation are presented. The progressive review of the literature which was carried out is described, and findings from unstructured interviews with industry practitioners are reported.

The literature review involved a variety of archival research techniques. On-line searches of library catalogues, such as Construction & Building Abstracts and Architectural Publications Index, were carried out. Also, the Internet sites of publishing houses and industry bodies were searched to identify relevant titles. In addition, guidance on literature sources was sought from academics and practitioners. Books, journal articles and academic papers were obtained from the libraries of universities and professional bodies. During the literature review, the following five themes emerged:

- continued low productivity and poor quality in the construction industry;
- improved productivity and quality in the manufacturing industry;
- lack of DFM application in the construction industry;
- characteristics of manufacturing design and construction design;
- the affect of design on productivity and quality.

These themes are explored in the following five sections of this chapter. Please note that although procurement and production are often referred to in the discussion, it is not the purpose of this chapter to debate these issues. The research was focused on the use of design to improve productivity and quality in the construction industry. Consequently, procurement and production are discussed only where this is necessary to explain how design, and in particular DFM application, can improve construction productivity and quality.

2.2 Continuing Low Productivity and Quality in Construction

In the UK, construction expenditure makes up over half of national investment and contributes eight percent of gross national product (Olomolaiye *et al*, 1998). Consequently, low construction productivity and poor construction quality are considered to be very significant both by government (Allmon *et al*, 2000) and the private sector (Wong *et al*, 2000). For example, since the Second World War there have been nine government reports dealing with the need for productivity and quality to be improved in the UK construction industry (Flannagan *et al*, 1998).

As long ago as 1962, the construction industry was being criticised by government for using out-of-date procedures (Emmerson, 1962). Worse followed when in 1966 it was highlighted that, "the construction industry is characterised by endemic crisis" (Tavistock, 1966). Almost thirty years later, it was reported by Latham that the fundamental problems which have affected the industry since the 1960's had not been addressed. In addition, it was stated that the challenges facing construction had become even greater because of the pace of technological change and diversity of new components. It was concluded that a thirty percent increase in construction productivity was essential, and that urgent action was needed to tackle poor quality (Latham, 1994). The most recent government report, "Rethinking Construction" (DETR, 1998), states that, ... *more than a third of major clients are dissatisfied with contractors' performance in keeping to the quoted price and time, and delivering a final product of the required quality.* This statement is consistent with the findings of other research carried out in recent years (Ball, 1988; BEDC, 1987; CCF, 1998; Harvey and Ashworth, 1993; McCabe, 1998).

These observations were echoed by building design and building production practitioners during exploratory interviews. The interviews involved one architect, one consulting engineer, one interior designer, one construction manager and one commercial manager. All the interviewees were professional contacts of the author. They were selected because of their high level of training and experience. Details of how the interviews were conducted are provided in Appendix A. During the interviews, there was a common opinion that the productivity and quality problems of the construction industry were not getting any better. Further, the interviewees believed that they were having to work harder just to maintain existing standards of productivity and quality.

2.3 Improved Productivity and Quality in Manufacturing

The Report of the Construction Industry Task Force, Rethinking Construction, which was cited above, states,

.... in the manufacturing industry there have been increases in efficiency which a decade or more ago nobody would have believed possible ....

These increases in efficiency include achievements such as British Steel quadrupling their productivity (Taylor, 1996) and Toyota cutting defects by two thirds (Madigan, 1997).

Even general manufacturing text books highlight the contribution of DFM methodologies to the productivity and quality improvements achieved in the manufacturing industry. For example, the text book, Operations Management (Vonderembse and White, 1991), provides several DFM examples, including how Texas Instruments cut assembly time for an infra-red sighting mechanism from 129 minutes to 20 minutes. More focused text books, such as New Wave Manufacturing Strategies (Francis, 1994) and Product Design and Development (Ulrich and Eppinger, 1995) each devote a whole chapter to DFM. The more detailed analysis of DFM, which was carried out later in the research, is reported in Chapter 4.

The texts referred to during exploratory research do not provide a detailed description of proprietary DFM methodologies. However, they explain that DFM provides a rule- and metric-based approach for integrating production best practice into designs. Design engineers can use DFM metrics to assess the production implications of their design decisions straight away. Further, design engineers can follow DFM rules to make their designs easier to produce. As described below, this rule- and metrics-based approach is very different from the people focused approach which has been repeatedly recommended for the construction industry in government reports and academic papers. Although DFM application can be enhanced by design engineers working with production engineers, successful application does not depend on this type of collaboration, because production knowledge is contained within DFM rules and metrics.

2.4 Lack of DFM Application in the Construction Industry

2.4.1 Little understanding of standard production design rules and metrics

Attempts to better integrate building production best practice into building designs can be traced back to The Emmerson Report (1962). This identified a lack of confidence between architect and builder that amounted, at worst, to distrust and mutual recrimination. The Report recommended better cohesion between the architect, contractors and sub-contractors.

This people focused approach towards integrating production best practice into building designs has persisted until the present day. Production knowledge is seen to be locked in the memories of individuals. Consequently, the integration of production best practice is viewed as depending on having experienced production people contribute to building design (Anderson *et al*, 2000). This people focused approach has been recommended continually for some forty years. For example, the Banwell Report (1964) suggested the breaking down of divisions between design and construction professionals. Subsequently, another major report (NEDO, 1967) advocated early collaboration of the contractor in the design team. In spite of these repeated recommendations, in 1991 it was reported that there was still a need for contractors to have earlier input to building designs (CSSC, 1991). By 1998, recommendations for early involvement had been extended to include building component manufacturers as well as building contractors (RCF, 1998).

Following these continuing recommendations for increased cohesion between building design personnel and building production personnel, there has been considerable interest in concurrent engineering amongst construction academics in recent years (Jaafari, 1997; Jamieson, 1997; Jones and Riley, 1994; Love *et al*, 1998). Concurrent engineering relies on designers from all phases of the product life-cycle working in parallel (Eldin, 1997). It involves designing products and their related processes and systems simultaneously to achieve the best available balance between form, function and production. This is a balance which seldom achieved in the design of buildings (Ishai, 1989; Trinh and Sharif, 1996). In particular, considerable research has been carried out concerning the development of software systems for concurrent development of building design drawings (Amor and Hosking, 1994; Mitev *et al*, 1996; Sandakly *et al*, 1998; Tonarelli *et al*, 1995). Electronic data exchange in concurrent engineering is of particular interest to researchers (Choi and Ibbs, 1994; Ott, 1998; Rijn *et al*, 1998). All of this research is concerned with how to improve people focused approaches towards integrating production best practice into building designs.

None of the reports and research discussed above advocate the rule- and metrics-based approach which has been successfully realised by DFM in the manufacturing industry. In the construction industry, production design rule- and metric-base methodologies are not well-known. This was highlighted by the responses of practitioners during exploratory interviews. Even though all the interviewees had considerable experience of working for large organisations, none of them had heard of formal production design methodologies. Further, interviewees had considerable difficulties in grasping the concept that production knowledge could be recorded for universal use in the form of rules and metrics. When the subject was raised, they all made reference to "buildability". This vague concept, which in the construction industry could easily be confused with DFM, is discussed below.

2.4.2 Comparing DFM to buildability

In construction, concern for the design / production relationship and its consequences is frequently encapsulated in the term, buildability (Chandler, 1989). Moore and Tunnicliffe (1994) defined buildability as "that design philosophy which recognises and addresses the problems of the assembly process in achieving the construction of the designed product, both safely and without resort to standardization or project level simplification". The words, ".... design philosophy which recognises and addresses ...." suggest that the term buildability can be thought of as a design method as well as a production objective. In contrast, to manufacturers factors such as assemblability are solely measurable production objectives, which cannot be achieved without a formal design method. Assemblability is measured by comparative assembly times and costs. Adherence to DFM design improvement rules is the method by which improved assemblability is achieved. Although, there are various recommendations about how building design and building production can be integrated (Alshawi and Underwood, 1996), such as "simplified designs", and "use suitable materials" (Adams, 1989) these recommendations constitute neither a measurable production objective nor a formal design method.

It has been suggested that there is no simple answer to evaluating buildability because of the complexity of the construction process (Gray, 1983). However, in the manufacturing industry, DFM has been used successfully to evaluate and improve the assemblability of a wide range of complex goods, including aircraft (Weber, 1994), cars (Kobe, 1992), and computers (Digital, 1990). Like buildings, these goods vary considerably: for example, aircraft are large, have a high number of components, and a life-cycle measured in years, whilst computers are much smaller, have far fewer components, and a much shorter life-cycle. Furthermore, the production systems used in the manufacture of these goods are often very complex and are frequently changed to meet new market pressures (Gann, 1996). In spite of product and processes complexity, production objectives in the manufacturing industry are defined in measurable terms, and DFM provides a very successful formal production design method for achieving them. For example, IBM has reported a cut in printer assembly time from thirty minutes to three minutes as a result of applying DFM (Vonderembse and White, 1991).

In contrast, after many years, process complexity is still seen as a barrier to defining buildability (CIRIA, 1983), and production design procedures associated with buildability remain largely informal and reliant on intuitive application. Such approaches to integrating design and production may have been effective when craft practices and a few versatile materials were used to construct buildings. However, the extent and speed, of technological innovation means that building designers now have to chose from a rapidly increasing number of high performance components and specialist processes (Moore, 1996).

Compared to traditional materials and parts, newer components can be more difficult to adapt or replace quickly, and their properties are not always compatible with traditional site practices. This means that practical experience can have a narrower application and a shorter life-span (Hyde, 1995), which makes it difficult for even the most experienced architects and consulting engineers to integrate production best practice into their designs. This may explain why, in spite of increased attention to buildability during the past twenty years, the proportion of construction productivity and quality problems attributable to inadequate design has remained at about fifty percent (BRE, 1981; Barber *et al*, 2000).

2.4.3 Little evidence of DFM application in the construction industry

There has been some recognition of DFM amongst construction industry academics in recent years. In particular, researchers at Cranfield University have considered "design for manufacture thinking" as a way of improving the efficiency of the design decision making process (Morris *et al*, 1998). The outcome of their work is a design decision planner which provides, "a mechanism for checking that the decisions have been taken at the correct time and the design process is on track" (Rodgerson *et al*, 1999).

Although no evidence was found of DFM methodologies being applied to entire buildings, one example of application to building components was found. These were electric shower heater units which are designed and manufactured by Caradon (CSC, 2000). The result of this application was a thirty-two percent parts reduction and a twenty-three percent reduction in assembly time. These shower heater units are the type of standard discrete engineered goods to which existing DFM methodologies are typically applied.

Having identified the effectiveness of DFM as means of improving productivity and quality in the manufacturing industry, and its lack of application in the construction industry, exploratory research turned to an analysis of the characteristics of construction design and manufacturing design.

2.5 Characteristics of Construction Design and Manufacturing Design

In order to determine to what extent, if any, construction design and manufacturing design are different, factors which determine the nature of design information and design activities were examined. This work revealed two significant factors: design leadership and design reuse. These factors are examined below to inform discussion of the differences between construction design and manufacturing design.

2.5.1 Design leadership: comparing customer-led with producer-led design

Producer-led design often results in *pre-order* design certainty. Design engineers who develop manufactured goods, such as cars, create a standard pattern of space which delivers the *general functionality* required by a *customer type*. They fix the forms and finishes of each car, and the forms, finishes, configurations and interfaces of every component used to manufacture each car. Design is led by the producer, not the customer, and as a result, design is certain before any orders are received. As a result, it is technically **feasible** to develop:

a) **product-specific production information systems; and**

b) **product-specific mass produced components with product-specific assembly tooling** (Gann, 1996).

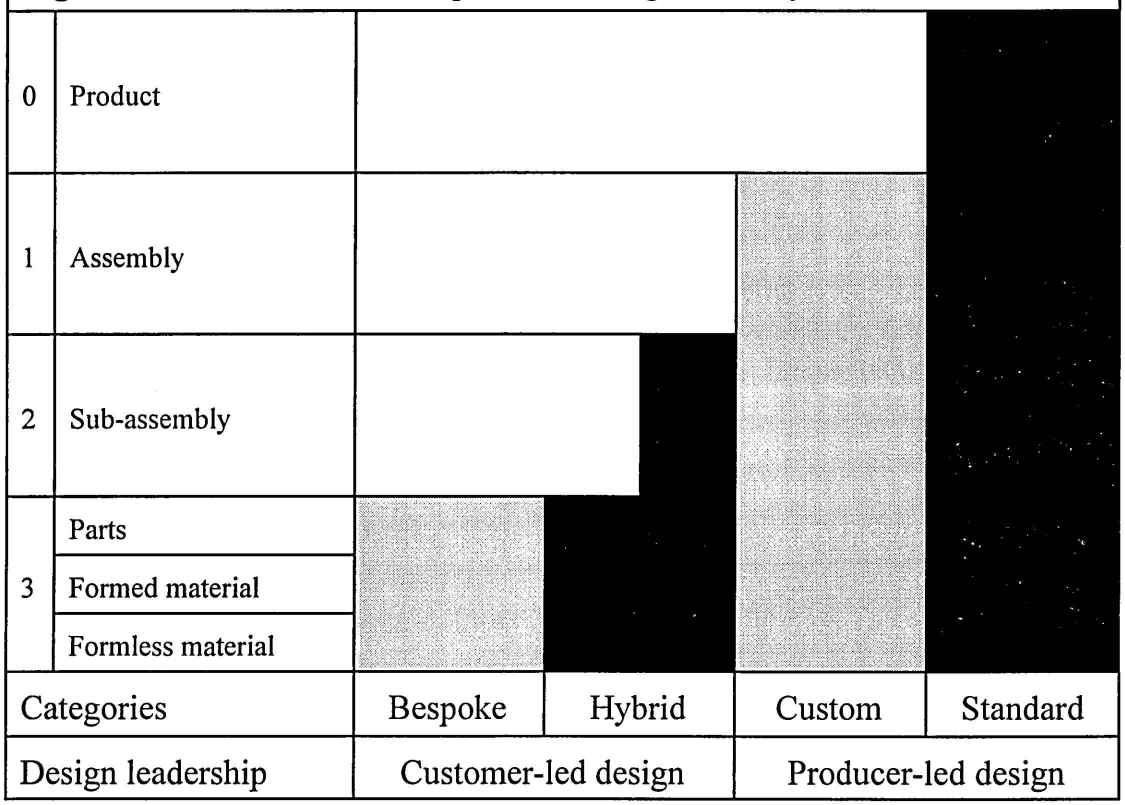
In contrast, customer-led design often results in *post-production* design certainty. Building design is usually customer-led, with architects and consultant engineers being employed to create patterns of space which deliver the *specific functionality* required by a *specific customer* (Gray, 1996). As a result, it is difficult for them to define the designs of all components with certainty before an order is issued for construction. This is because the client's objectives, budgets and/or preferences may change during both design and construction (CSSC, 1996). Further, as shown in Figure 2.1 below, they may not be able to define the designs of all component interfaces with certainty until as-built drawings are issued (Cox *et al*, 1999).

Figure 2.1: Timing of design certainty

Design outputs	Bespoke / hybrid buildings	Standard / custom goods
Component forms and finishes	*During construction*	*Before order*
Component configurations and interfaces	*After construction*	*Before order*

Customer-led design often results in **bespoke** and **hybrid** goods, whereas producer-led design often results in **standard** and **custom** goods. As shown in Figure 2.2, these words are used by the author to define the levels of pre-order design certainty which can be achieved. Throughout this thesis, the term design certainty means full and fixed definition of forms and finishes. The word "standard" is used by the author to identify that design is certain at product level before any

Figure 2.2: Different levels of pre-order design certainty



orders are received. For example, the design of every Dyson vacuum cleaner is certain at product level before each order is received. The word "bespoke" is used by the author to identify that only the design of loose parts and materials are certain before an order is received. For example, if plasterboards and nails are used in the construction of a bespoke building their design is certain before they are ordered.

Their forms are well known as standard board and fixing sizes. The word "hybrid" is used by the author to identify that a design comprises standard sub-assemblies with bespoke interfaces. The word "custom" is used by the author to identify that design is certain at assembly level before any orders are received. For example, when choosing a new car, a buyer can select and configure a range of assemblies, such as engines and bodies. As shown in Figure 2.3, bespoke, hybrid, custom and standard goods are designed in both the manufacturing industry and the construction industry. It is important to recognise that these are design certainty, not design

Figure 2.3: Examples of different categories of goods

Bespoke	Hybrid	Custom	Standard
Ship	*Home IT system*	*Volume car*	*Vacuum cleaner*
HQ building	*Hotel chain building*	*Drive-thru restaurant*	*Portable office*

complexity categories. For example, although both a home IT system and a hotel chain building can be hybrid, the bespoke building interfaces between standard hotel sub-assemblies, such as bathroom pods, are likely to be far more complex than the bespoke IT system cabling interfaces between standard computer hardware.

2.5.2 Design reuse: comparing location-specific with market-specific design

Market-specific design often results in *high volume* goods. A market can be global with millions of customers. As shown in Figure 2.4 below, this means market-specific design can lead to high repetition of the pre-order design certainty achieved by producer-led design.

Demand is often high enough to make it economically **viable** to develop:

a) **product-specific production information systems; and**

b) **product-specific mass produced components with product-specific assembly tooling** (Gann, 1996).

Figure 2.4: Repetition of design certainty		
Design outputs	Bespoke / hybrid buildings	Standard / custom goods
Component forms and finishes	*Low*	*High*
Component configurations and interfaces	*None*	*High*

Location-specific design often results in *low volume* goods. Even when a construction client, such as a hotel chain, wishes to have a standard building designed for repeated construction, this is seldom possible because each building encloses a *specific space* which is defined by its *specific location*. For example, the footprint of a building is constrained by location-specific factors, such as adjacent structures and natural features. Similarly, the colours and textures of its finishes are constrained by planning laws which are intended to ensure that environmental considerations are respected. Many new buildings are hybrid because, in order to satisfy irregular boundaries, standard sub-assemblies have to be installed with bespoke interfaces and/or finishes. Further, bespoke component interfaces are also required because tolerances for construction operations, such as excavation, can lead to significant differences between actual and drawn building dimensions. Building refurbishments are bespoke, because bespoke interfaces are the only means of achieving a coherent appearance between new components and an original structure and fabric. Also, to meet market pressures for increased functionality, designers have to specify the latest high performance components. As a consequence, many of the design details for each new building and building refurbishment will be original. All of these factors limit the ability of architects and consultant engineers to design buildings which can be constructed in many locations. This, in turn, limits opportunities for them to work with manufacturers in the design of mass produced, building-specific, components. Hence, location-specific design results in there being little, or no, repetition of the post-production design certainty which results from customer-led design.

2.5.3 Similarities between construction design and manufacturing design

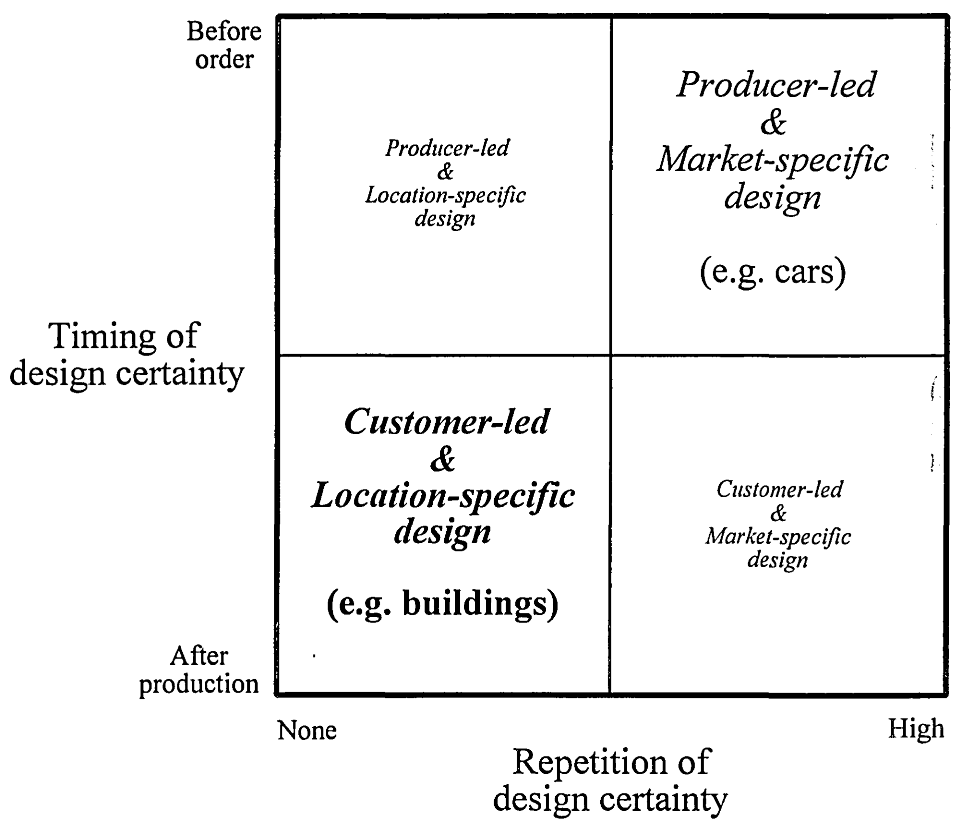
The preceding analysis suggests that it is design leadership and design reuse which determine what type of procurement and production arrangements are feasible and viable, rather than the industry in which design takes place. Design could appear to be fundamentally different in manufacturing and construction because, as discussed above, design in the construction industry is customer-led and location-specific more often than in the manufacturing industry. Consider the example of McDonald's drive-thru restaurants (CIRIA, 1999). Only the design of the foundations of these buildings is location-specific. This has made it both feasible and viable for building-specific assemblies and construction processes to be developed. As a result, the previous twenty-six week construction programme has been reduced to less than two weeks and quality has increased. Another example of these types of improvements is the cost of constructing BP petrol stations being reduced by twenty-six percent between 1997 and 1999 (DETR, 1999a). Again, in this case only the design of building foundations is location-specific.

2.6 The Affect of Design on Productivity and Quality

2.6.1 The affect of design information on procurement and production

The affect of design information and design activities on procurement and production methods are now analysed in more detail. As discussed above, and shown in Figure 2.5, when design is customer-led and location-specific there is little, or no repetition, of the building design certainty which is achieved either

Figure 2.5: The timing and repetition of design certainty



during or after production. This often leads to new production information being prepared during design. New architectural / engineering drawings, specifications and bills of quantities being prepared for each bespoke and hybrid building.

Similarly, new workshop drawings, cutting lists and purchase orders are prepared by manufacturers of bespoke and hybrid building components for each order. As customers demand more sophisticated buildings, and the materials and parts required to produce them become more diverse, the time and cost of preparing information increases. The time taken to prepare new information can reduce the time available for component manufacture and building construction. This can often result in operatives having to work overtime and hurry their tasks, which can lead to quality problems. In contrast, producer-led market-specific design results in there being high repetition of the design certainty which is achieved before any orders are received. This makes it both feasible and viable for marketing / assembly companies, which produce standard and/or custom goods, to develop the types of production information with their manufacturers which are listed in Figure 2.6. All

Figure 2.6: Types of information

Information	Bespoke / hybrid building	Standard / custom goods
Design	*New drawings / specifications*	*Fixed engineering bills of materials*
Planning	*New programmes*	*Fixed process routes*
Procurement	*New bills of quantities*	*Fixed manufacturing bills of materials*

of these can be used for every order which is received for a particular product. Order-specific manufacturing information is generated by using computer systems to perform the component configurations which are defined in engineering bills of materials. Material requirements are defined by manufacturing bills of materials and capacity requirements are defined in process routes. Component forms, finishes, configurations and interfaces are defined with sufficient accuracy and precision in bills of materials and process routes to ensure that goods are produced right first time every time. It is important to recognise that design certainty can be achieved without the design ever having been produced. For example, during the development of a new car model, only a few of the thousands of options which will be available to buy are produced. Nevertheless, by the end of product development, the design of every potential combination of body shapes, engine sizes, colours and accessories is certain. Where marketing / assembly companies are operating globally, it is imperative that production information can be used easily and reliably by component manufacturers and assembly plants in different parts of the world. To achieve this requires up-front investment in production information which far exceeds the investment required for traditional experienced-based approaches to preparing production information.

UK construction companies and building component manufacturers may buy in materials and parts from companies which face global competition, but they are less likely to have to compete against foreign marketing / assembly businesses than a UK car company. Figure 2.7 below, shows the different levels of competition likely to be experienced.

Figure 2.7: Levels of competition

Bespoke / hybrid building			Bespoke / hybrid building component		
0	*Office with curved entrance*	*National*	*0*	*Curved reception desk*	*National*
1	*Reception area*	*National*	*1*	*Curved base unit*	*National*
2	*Ceiling*	*National*	*2*	*Curved drawer unit*	*National*
3	*Metal interlocking ceiling tiles*	*European*	*3*	*Curved metal brackets*	*Local*
3	*Plasterboard*	*European*	*3*	*MDF; veneers*	*Global*
3	*Plaster and paint*	*Global*	*3*	*Adhesive; lacquer*	*Global*

Architects and/or consulting engineers may participate in an international competition to design a prestigious building, but they are at site to explain and expand the production information which they have prepared. In contrast, the production information generated during the design of standard or custom goods can be used without the design engineers responsible being present. All of these factors result in the differences in design information shown in Figure 2.8 below.

Figure 2.8: Comparison of design information in construction and manufacturing

Factor	Bespoke / hybrid buildings		Standard / custom goods
Timing	*During and after construction*	→	*Before orders are received*
Use	*Once*	→	*Often*
Completeness	*Many details finalised at site*	→	*Full*
Accuracy	*Inaccuracies resolved at site*	→	*Total*
Cost	*Can be carried by one project*	→	*Need to be amortised over many sales*

2.6.2 The affect of design activities on procurement and production

As shown in Figure 2.5 above, producer-led market-specific design results in the forms, finishes, configurations and interfaces of components being certain before every one of a high volume of orders is received. This enables a design engineer with overall responsibility for the development of a standard or custom product to control the following activities:

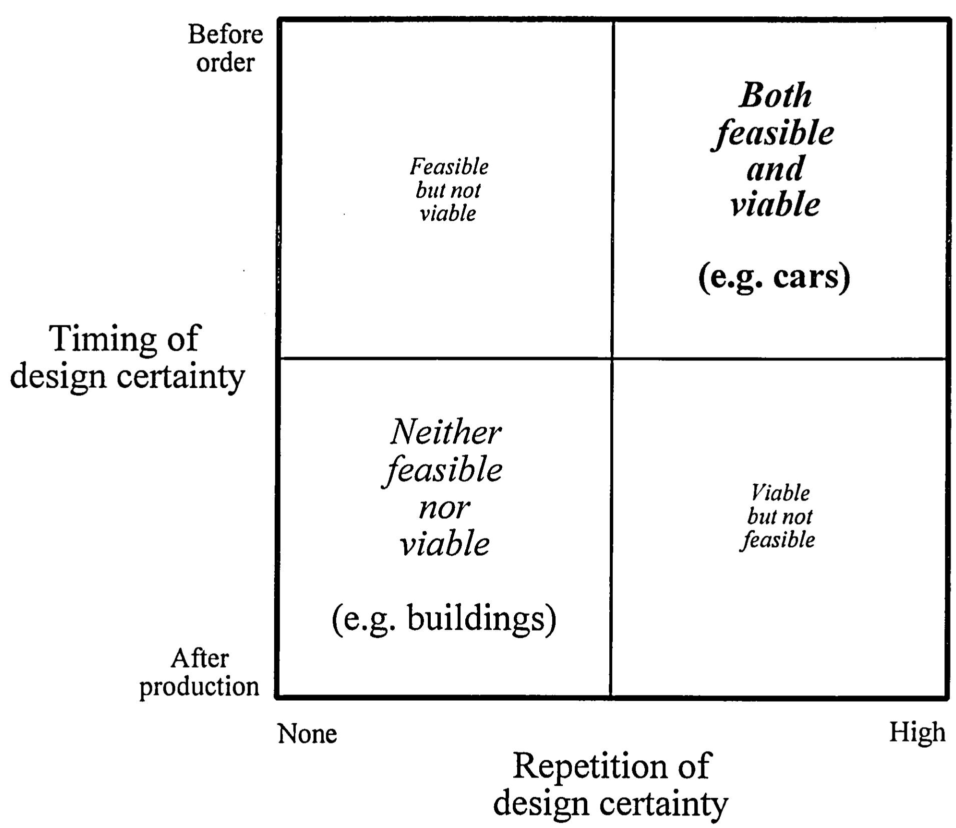
- total design of the product;
- design of mass-produced product-specific sub-assemblies and assemblies;
- selection of component-specific manufacturing processes and plant; and
- optimisation of product-specific assembly processes, plant and tooling.

In contrast, a building designer with overall responsibility for the design of a bespoke or hybrid building is only able to control the following activities:

- **agreement** of the building's design with client and planning authorities;
- **selection** of mass-produced standard or custom materials and parts; and
- **design of one-off** building-specific bespoke and hybrid sub-assemblies and assemblies (Morton and Jagger, 1995).

Design engineers who lead the development of a standard or custom product are able to carry out a wider range of activities because, as shown in Figure 2.9, it is both feasible and viable to develop mass produced product-specific components.

Figure 2.9: Mass produced product-specific components



Further, it is feasible to develop a design comprising only discrete components which are specific to a family of products, such as a range of car models These components have few and certain configuration and interface options. Examples are shown in levels 1, 2 and 3 of Figure 2.10.

Figure 2.10: Fixed vertical standard / custom goods component relationships

Component levels		Automotive example	Building example
0	Product	*A car*	*Portable office*
1	Assembly	*Axle of a new car model*	*External door set for portable office*
2	Sub-assembly	*One of the wheels on the axle*	*Door set frame*
3	Part	*The tyre on the wheel*	*Door frame jamb*
4	Material	*Rubber used to manufacture tyre*	*Aluminium used to manufacture jamb*

Where assembly companies provide component manufacturers with high demand, it is viable for them to develop mass produced, product-specific, discrete sub-assemblies and assemblies. In contrast, the aesthetic, geometric and dimensional uncertainties arising from customer-led location-specific design necessitate the use of materials to form interfaces between parts. In building design, materials, such as plasterboard, are used to provide a coherent appearance for irregular interfaces between discrete components, such as square ceiling tiles and curved curtain walling sections. Also, formed materials, such as vinyls, and formless materials, such as sealants, are used to construct building details that cannot always be achieved by discrete components, such as shower trays, which have fixed forms and finishes. Materials are placed with installed parts in the sets of relationships shown in Figure 2.11 below.

Figure 2.11: Variable mixed bespoke / hybrid building component relationships			
Component levels		Building example	Building component example
0	Product	*Office with curved entrance*	*Curved reception desk*
1	Assembly	*Reception area*	*Curved base structure*
2	Sub-assembly	*Ceiling*	*Curved drawer unit*
3	Parts	*Metal interlocking ceiling tiles*	*Curved metal brackets*
3	Formed material	*Plasterboard*	*MDF; veneers*
3	Formless material	*Plaster and paint*	*Adhesive; lacquer*

As a result of these variable and mixed component relationships, building components have many and uncertain configuration and interface options. The design uncertainty shown in Figure 2.12 below, leads building component

Figure 2.12: Building component design uncertainty		
Design outputs	Bespoke and hybrid buildings	Standard and custom goods
Component forms and finishes	*Many and uncertain options*	*Few and certain options*
Component configurations and interfaces		

manufacturers to develop either a range of mass produced, standard and custom, materials and parts, or the capability to produce bespoke and hybrid sub-assemblies and assemblies. Building designers' influence over the development of standard materials and parts being limited to possible participation in manufacturers' market research. Building designers have more control over the forms and finishes of bespoke sub-assemblies and assemblies, but these are not mass produced using product-specific plant and tooling. As shown in Figure 2.13 below, the design of mass produced building-specific components, production plant and tooling, are seldom building design activities. General purpose mass-produced components

Figure 2.13: Comparison of design activities		
Design activity	Bespoke/hybrid buildings	Standard/custom goods
Design of bespoke components	*One-offs*	*None required*
Design of mass-produced components	*General-purpose*	*Product-specific*
Design of manufacturing processes and plant	*General-purpose*	*Component-specific*
Design of construction/assembly, processes and plant	*General-purpose*	*Product-specific*

(e.g. concrete blocks), general purpose plant (e.g. excavators), and general purpose tooling (e.g. an excavator bucket) tend to be used instead. This use of general purpose components, plant and tooling contrasts with the development of product-specific mass-produced components and product-specific assembly tooling, which takes place during the design of standard and custom goods. Long-term, collaborative, high investment procurement and production arrangements are needed to achieve these product-specific developments. These arrangements are feasible and viable when design is producer-led and market-specific.

2.6.3 The affect of design on productivity and quality

The foregoing analysis suggests that, from the perspective of productivity and quality improvement, design leadership and design reuse are more significant than the industry in which design is carried out. This is because, it is design leadership and design reuse which determine a) what types of design information, and b) what types of design activities, are feasible and viable. For example: the pre-order design certainty achieved by *producer-led design* makes development of: a) product-specific production information systems; and b) product-specific mass produced components with product-specific assembly tooling, feasible. High repetition of design certainty achieved by *market-specific* design makes their development viable. In any industry: a) product-specific information systems can radically reduce the time taken to generate production information; b) mass production of product-specific components can cut manufacturing costs, and use of product-specific tooling can increase product quality as well as reduce assembly times and costs. It is design which determines what procurement and production options are feasible and viable. Figure 2.14, illustrates how procurement and production link design to productivity and quality.

Figure 2.14: The affects of producer-led market-specific design on productivity and quality

DESIGN LEADERSHIP AND REUSE	
Producer-led design	***Market-specific design***
⇓	⇓
Pre-enquiry design certainty	***High repetition*** design certainty
⇓	⇓
Certain component form and finish options	***Few*** component form and finish options
⇓	⇓
Fixed component relationships	***Vertical*** component relationships
⇓	⇓
PROCUREMENT AND PRODUCTION OPTIONS	
Technically Feasible	***Economically Viable***
Product-specific information systems	Product-specific information systems
Product-specific mass-produced assemblies	Product-specific mass-produced assemblies
Component-specific manufacturing plant	Component-specific manufacturing plant
Product-specific assembly tooling	Product-specific assembly tooling
⇓	⇓
PRODUCTIVITY AND QUALITY IMPROVEMENT OPPORTUNITIES	
Reduce Time required to generate Production Information	
Reduce Time required to Manufacture Components	
Reduce Time required to Assemble Products	
Improve Quality of Production	

When design is producer-led and market-specific a wide range of procurement and production options are available, from job assembly processes with general purpose components and tooling, to flow assembly processes with product-specific components and tooling. In contrast, wherever design is customer-led and location-specific, (e.g. bespoke and hybrid goods), radical productivity and quality improvements are far harder to achieve. This is because, as explained above, and illustrated in Figure 2.15, the development of product-specific production information systems, mass-produced product-specific components, and product-specific assembly tooling is neither feasible nor viable. As explained previously,

Figure 2.15: The affects of customer-led location-specific design on productivity and quality

DESIGN LEADERSHIP AND REUSE	
Customer-led design ⇓ ***Post production*** design certainty ⇓ ***Uncertain*** component form / finish options ⇓ ***Variable*** component relationships ⇓	***Location-specific design*** ⇓ ***Little, or no, repetition*** design certainty ⇓ ***Many*** component form / finish options ⇓ ***Mixed*** component relationships ⇓
PROCUREMENT AND PRODUCTION OPTIONS	
Technically Feasible General purpose information systems; General purpose mass-produced parts; One-off assemblies; General purpose manufacturing plant General purpose assembly tooling ⇓	***Economically Viable*** General purpose information systems; General purpose mass-produced parts; One-off assemblies; General purpose manufacturing plant; General purpose assembly tooling ⇓
PRODUCTIVITY AND QUALITY IMPROVEMENT OPPORTUNITIES	
Limited Productivity and Quality Improvement Opportunites	

when design is customer-led and location-specific both procurement and production are more likely to be carried out on a one-off basis, with materials and parts being selected from catalogues and purchased from merchants. These types of approaches are so well-established and widely used, that becoming more proficient in their execution is unlikely to yield significant productivity and quality improvements.

2.7 Definition of Research Questions

The conclusions which arose from consideration of exploratory research findings are listed below.

- It is widely recognised that there is a need for construction productivity and quality to be improved.

- DFM has been so successful in improving productivity and quality in the manufacturing industry that even if only some of these improvements could be emulated in the construction industry they would still be significant. For example, production cost reductions of up to fifty percent have been reported as a result of DFM application in the manufacturing industry (Ulrich and Eppinger, 1995). Therefore, if DFM application in the construction industry was only a quarter as successful, then significant production cost reductions would still be achieved.

- There is little evidence of DFM being applied to building components and no evidence of DFM being applied to entire buildings. Further, no evidence was found of other formal production design methodologies being used in the construction industry.

- Building, and building component, design are often customer-led and location-specific. As a result, the types of design information generated tend to be different to those prevalent in the design of standard and custom manufactured goods.

- Building, and building component, design are seldom producer-led and market-specific. As a result, the types of design activities carried out tend to have less potential to improve productivity and quality than those common in the design of standard and custom manufactured goods.

The first three conclusions encouraged more research into the application of DFM to buildings and building components. However, the final two conclusions raised the following questions:

- how can DFM be *applied* during building component design and building design?, and
- how can DFM application be *successful* in improving the productivity and quality of building component production and building construction?

Further literature review found no evidence of investigation of these two questions. Hence, answering these fundamental questions became the focus of the research which was subsequently carried out.

2.8 Chapter Conclusion

In this chapter, the issues listed below have been discussed. These emerged as being significant during literature review.

- Continued low productivity and poor quality in the construction industry.
- Improved productivity and quality in the manufacturing industry.
- Lack of DFM application in the construction industry.
- Characteristics of manufacturing design and construction design.
- The affect of design on productivity and quality.

The conclusions which arose from analysis of these issues have been described, and the two research questions which were subsequently defined have been stated.

All subsequent research concentrated on investigating the potential for successful application of DFM in the construction industry. However, it is not the purpose of this thesis to suggest that DFM alone can solve all the productivity and quality problems of the construction industry. The research sought to determine how DFM can make a significant contribution to improving productivity and quality in the construction industry. In construction, there are some problems which may never be completely eradicated by better design. For example, the productivity and quality of building foundation construction is always likely to be higher in summer, than in winter when hands are frozen and legs are knee deep in mud (Ferguson, 1989).

3.0 Research Methodology

3.1 Introduction

The research methodology is a means to an end: it is not an end in itself. The purpose of a research methodology is to provide a means of ensuring valid answers to the research questions. The research methodology comprises the research strategy and the research instruments used to fulfil that strategy. To be effective, the research questions, research methodology and research resources must all be well-matched (Manstead and Semin, 1988). This chapter begins by outlining fundamental research design issues. Then, the strategy selection process and the research methodology which was used are described in detail. Samples of the research instruments used are included in the Appendices. The relevant Appendices are referred to in subsequent chapters as the research is described.

3.2 Research Design Issues

3.2.1 General research design issues

There are two main research traditions. One is called positivistic, hypothetico-deductive or quantitative, and the other, is known as interpretive, ethnographic or qualitative. Spradley (1980) compares positivistic researchers to petroleum engineers, who with the aid of maps, go out to find something specific. In contrast, interpretive researchers are compared to explorers, who venturing out into unknown territory, take the compass readings which enable the maps to be drawn up. The positivistic approach is often regarded as starting with a theory, from which a hypothesis is deduced and tested. With the interpretive approach, the research gives rise to the theory. This approach is supposed to be purely inductive, with generalisations being formed in an unbiased way from sensory data. However, when carrying out such research it can be difficult to ignore the theories that one already knows about (Glasser and Straus, 1967).

It has been argued that many of the differences between the two research traditions can be viewed as technical rather than epistemological (Bryman, 1988). Further, it has been suggested (Parke, 1993) that both extremes are untenable and the process of on-going theory advancement requires continuous interplay between the two. This perspective supports the selection of methods associated with either tradition to meet the needs of the research (Miles and Huberman, 1984).

It has been reported that much construction research uses deductive methodologies, which involves the formulation of theories followed by the deduction of empirical consequences from large samples (Seymour and Rooke, 1995). However, it has also been suggested that there is a trend towards the use of inductive methods to better capture the complexity and dynamism of construction settings (Love *et al*, 1999).

3.2.2 Specific research design issues

As described in Chapter 2, the research began with exploratory literature review and practitioner interviews focused on:

the use of design to improve construction industry productivity and quality.

The research focus had emerged after many years of industry experience combined with vocational, professional and post-graduate distance learning. It was the result of personal reflection stimulated by practical difficulties encountered during building component production and building construction. An inevitable consequence of this research focus is the need for industry involvement. In the preceding chapter, it was identified that "the construction industry is characterised by endemic crisis". In such an environment, there are many threats to research validity which can restrict research strategy options and outline the design of research instruments. These are described in subsequent sections of this chapter.

3.3. Research Strategy Selection

3.3.1 The timing of research strategy selections

Research strategy selections were made at the following four key points:

- when the research focus had emerged;
- when the two research questions had been defined;
- when the research hypothesis had been generated; and
- when the results from hypothesis testing had been analysed.

Figure 3.1 below, provides a summary of the research strategies selected. It shows when strategy selections were made and the outputs which were required from these strategies.

Figure 3.1: Research strategies selected

Timing of strategy selection	Strategy selected	Required research output
Research focus emerged	*Survey*	Research questions
Research questions defined	*Survey*	Research hypothesis
Research hypothesis generated	*Case study* *Action research*	Hypothesis tests
Hypothesis testing results analysed	*Survey*	DFM strategies for Construction

The strategies which were selected provided the framework within which research instruments were designed. Together these formed the research methodology. The strategy selection process is now described.

3.3.2 Strategy selected to define the research questions

When the research focus, *the use of design to improve construction industry productivity and quality,* had emerged, various preliminary research questions needed to be answered. These included, *where*, if anywhere, is design used to improve construction productivity and quality, and *who*, is involved in doing so? Yin (1989) recommends a survey strategy for determining answers to these types of questions. Oppenheim (1992) also advocates a survey design to answer questions which are concerned with description and enumeration. Similarly, Bell (1997) emphasises the appropriateness of a survey approach for fact finding.

These authors share a common agreement that other research strategies are less appropriate for these types of questions. For example, an experimental strategy requires the researcher to have control over events being investigated, and a case study strategy is better suited to gathering a large amount of very detailed information from a single case or a small number of related cases. In this exploratory work, the researcher had no control over *who*, if anybody, was using design to improve construction productivity and quality. Further, information needed to be gathered about the whole construction industry, rather than a single industry case, to find out *where*, if anywhere, design was being used to improve construction productivity and quality.

A survey offers the advantages of being relatively quick and cheap, making it both feasible and viable for single researcher studies. Also, provided that the survey instruments are designed and used properly, the personal influence of the researcher on the results can be slight (McNeill, 1995).

3.3.3 Strategy selected to generate the research hypothesis

As reported in Chapter 2, exploratory work led to definition of the two research questions stated below.

- How can DFM be *applied* during building component design and building design?
- How can DFM application be *successful* in improving the productivity and quality of building component production and building construction?

This was the second key point in the research. Yin (1989) recommends that these types of questions be dealt with by an experimental or case study research strategy. However, whilst the exploratory research reported in Chapter 2 had revealed that successful application of existing DFM methodologies was unlikely, it had not provided a theoretical base from which experiments or case studies could be carried out.

A more fundamental analysis of the content of DFM methodologies was required to identify those factors which are essential to DFM application and critical to DFM success. This had to be combined with a more detailed investigation of *where* such factors could be found in construction before a theoretical framework for the research could be developed. To use Spradley's analogy cited above, compass readings had to be taken to enable a map to be drawn up. This inductive research strategy was carried out using survey instruments to gather relevant data. Using this data, the potential for successfully applying DFM principles to different types of buildings was assessed. During this process, the hypothesis, *DFM principles can be applied successfully to building components and buildings*, was generated.

3.3.4 Strategy selected to test the research hypothesis

Generation of the hypothesis was the third key point in the research, and provided the theoretical base from which to address *how* can DFM be applied and *how* DFM application can be successful. It was at this stage that research strategy selection was most constrained by practical factors. In the "crisis" environment of the construction industry, most practitioners have to work long and hard just to fulfil orders and/or meet programmes (Cavill, 1999). Consequently, gaining the commitment of organisations to participate in research was a long process which included much correspondence, many dead ends and several false starts.

Even after the commitment of Contractor-X and Supplier-Y had been secured, all discussions, planning, and actions had to be seen clearly by participants as leading to beneficial practical outcomes. In spite of this, it was still very difficult for them to find time to participate in the research. For example, keeping an appointment with a researcher can cease to be a priority when a tender submission is late, or there has been an accident at site.

Although Yin (1989) recommends either a case study or experimental design for answering these types of questions, in this investigation, the research had to be designed around the few potential participants available without compromising rigour. The random sampling which is essential for true experimental designs was not possible. So, as described in detail later in this chapter, a quasi-experimental perspective was applied to the design of the interventions used to test the hypothesis. Again because of practical constraints, these interventions dealt with individual, rather than multiple, cases.

3.3.5 Strategy selected to develop DFM application in the construction industry

The final key point emerged when results from deductive research had been analysed and suggested that it is both technically feasible and economically viable to successfully apply DFM principles to building components and buildings. However, to answer the research questions strategies for the wider DFM application had to be developed and validated.

The development of the DFM strategy was a creative process following the type of thought pattern described by Cross (1996) as Recognition - Preparation - Incubation - Illumination - Verification.

To validate the strategy, various questions needed to be answered. These included, *where* and *how many* times would DFM principles be used? Yin (1989) recommends these types of questions, which seek to describe and enumerate, are best answered using a survey strategy. Other authors also advocate survey strategy to answer these types of questions (Malim and Birch, 1998). This is particularly true when general opinion is being sought about findings from specific studies (Giddens, 1998). The previous uses of survey instruments in this research were concerned with gathering descriptive information about past or current events. In contrast, at this stage of the research, the questions to be answered were concerned with possible future events. McNeill (1995) reports that survey methods are well suited to gathering opinions in this type of situation.

3.4 The Research Methodology

3.4.1 Defining the research questions

It has been suggested that the process of defining research questions can be viewed as often being non-linear, involving considerable uncertainty and intuition (Campbell *et al*, 1982). In this research, that was the case. As reported in Chapter 2, the process of defining research questions involved literature review and exploratory interviews.

Initially, literature review dealt mainly with text books, before moving on to journal articles and then academic papers. Exploratory interviews were carried out with a convenience sample of five construction industry practitioners: one architect, one consulting engineer, and one interior designer primarily involved in building design; and one construction manager and one commercial manager primarily involved in building construction. These industry practitioners are professional contacts of the author. They were selected because of their high level of training and experience. The interviews were conducted individually at the interviewees' offices. It was considered acceptable to use a convenience sample because at this stage the research was concerned with gaining an overall appreciation of the issues involved, rather than carrying out a detailed analysis. These interviewees did not participate in subsequent stages of the research because their existing relationships with the author could have resulted in them demonstrating positive bias.

As reported in Chapter 2, consideration of findings from literature review and exploratory interviews led to the definition of two research questions stated below.

- How can DFM be *applied* during building component design, and building design?
- How can DFM application be *successful* in improving the productivity and quality of building component production and building construction?

3.4.2 Generating the research hypothesis

Chapter 4 describes how the research hypothesis was generated. This involved the use of the following two survey methods listed below.

1) Literature from the manufacturing industry was reviewed to determine answers to the questions:

    what *design information* is essential to *DFM application*, and

    what *design activities* are critical to *DFM success*?

2) A field survey was carried out to determine evidence in the UK construction industry of:

    the design information found to be essential to DFM application, and the design activities found to be critical to DFM success.

The field survey comprised two sets of structured interviews and one postal questionnaire supported by follow-up interviews. All the participants in this field survey were either employed by, or carried out work with, Contractor-X.

Structured interviews were used to investigate what types of design information are in use, and to determine the availability of different types of design information. A postal questionnaire was used to ascertain what design activities are prevalent in the UK construction industry. Questionnaire follow-up interviews were carried out.

The need to use interviews to ask questions concerning design information was identified during exploratory interviews. These revealed that, whilst interviewees had a common vocabulary for design activities, they used many different terms to describe the same type of design information. For example, respondents used various terms, such as, data base, data file, and knowledge base to refer to indexed box files containing manufacturers' data sheets. In contrast, interviewees had a common understanding of terms relating to design activities, such as architectural design, structural engineering and interior design.

Interviews were carried out with three purposive samples of fifteen construction practitioners. Purposive sampling is very different to statistical generalisation from sample to population. It involves building up a sample which satisfies the needs of the specific research (Straus, 1987). Each sample comprised different people, but the same mix of practitioner types. In each sample, ten of the interviewees were consultants: three were architects, two were consulting engineers, one was a project manager, one was a design co-ordinator, one was a construction manager, one was a Mechanical & Engineering (M&E) services manager, and one was a commercial manager. Also, in each sample, five interviewees were employed by companies which design, manufacture, supply and/or place or install components. Each company specialises in one of the following building elements: substructure, superstructure, M & E, walls and ceilings, floors. The total sample over the three sets of interviews was forty-five industry practitioners.

For the self-administered postal questionnaire, a purposive sample of two hundred and sixty-seven was used. Respondents were categorised as consultants, building component manufacturers (i.e. companies which design, manufacture and supply only components,), and building component assemblers (i.e. companies which place and/or install components at site). A total of 127 (48%) responses were received. These included responses from twenty-five component manufacturers and from sixty-nine component assemblers. Thirty-three responses were received from consultants. Amongst the consultants surveyed there was an equal mix of architects, consulting engineers, project managers, construction managers and quantity surveyors.

All field survey participants have experience of working on individual buildings of over £50 million in value, under a range of traditional and innovative contract forms. Responses were received from organisations at all levels of construction supply chains, from raw material processors to clients' project managers.

3.4.3 Testing the research hypothesis: building component production

Chapter Five describes the action research intervention which was used to apply and evaluate DFM principles within Supplier-Y from June 1998 to September 2000. DFM principles were integrated into the operating systems of the business, and are now a routine part of its day-to-day enquiry and order processing.

An action research methodology was required because introducing standard DFM principles into the operating systems of a bespoke manufacturing business involves significant technological and organisational change. Action research methodologies add the achievement of change to the more conventional research goals of describing, understanding and explaining. In addition to monitoring and evaluating change, the researcher is actively involved in facilitating change. The researcher devises the change actions which are tried out by the people in the organisation. Data on the effects of these actions are collected by the researcher. Using these data, the researcher reviews, and where necessary revises, the principles upon which earlier actions were based. Then, the researcher devises more effective actions to be tried out by the organisation. This iterative cycle of *planning*, *acting*, *observing* and *reflecting* is continued until the relevant processes have been improved; the people in the organisation understand the processes; and the organisational environment in which the processes take place have been improved (Carr and Kemmis, 1986).

In this intervention, *planning* involved analyses of existing DFM methodologies, the business' outputs, and its operating environment; *acting* involved working within the business to guide the introduction of DFM principles;

observing involved monitoring the adoption and impact of DFM principles; and *reflecting* involved developing DFM principles to make them effective in the business' operating environment.

Obtaining valid findings from action research is difficult because the researcher has to facilitate change within an organisation, and demonstrate a causal relationship between that change and subsequent events (Rapoport, 1970). It has been suggested that action researchers often find themselves in dynamic settings which are not favourable to intellectual analysis (Popkewitz, 1984), and they can lose sight of the need for systematic methods (Atkinson and Delmont, 1985). However, when seeking to transfer a successful design method, such as DFM, from one industry to another, the practical guidelines and insights which action research yields can be extremely useful. In contrast, the more traditional approach of research followed by development followed by dissemination followed by adoption can be of limited usefulness in the UK construction industry, and has been subject to some criticism (Byrd, 1998). Over ninety-seven percent of businesses in the UK construction industry employ 25 people or less (DETR, 1999b), and there is little evidence to suggest that these organisations have the resources to make the transition from hearing about a concept during its dissemination to successfully adopting it. These small- and medium-sized businesses need to be told *how* they can adopt better methods not just what methods they should adopt.

The results of action research can deliver this type of implementation information, provided threats to research validity are recognised and dealt with. Tactics to overcome threats to research validity should be made explicit before the intervention begins and adhered to throughout. In this intervention, threats to *researcher objectivity* were counteracted by having changes in the business' performance measured by the business' accountant without the involvement of the researcher.

Threats to *research confirmability* were counteracted by applying the tenets of quasi-experimentation to the intervention. Quasi-experimentation includes introducing and manipulating an independent variable (in this case, DFM principles); measuring the effects of this manipulation on dependent variables (in this case, the productivity and quality of building component production); and controlling other variables (such as improvised design solutions by factory operatives). This definition of variables from the outset facilitates assessment of whether study findings flow from study data (Cook and Campbell, 1979).

An advantage of using an action research methodology in a production environment is that two threats to *reliability*, subject error and subject bias, are likely to be reduced. This is because subject errors and subject bias can lead to incorrect production information being generated, which in turn, can lead to expensive abortive production, and customer dissatisfaction with the business. Therefore, subject errors and subject bias are a threat to the business' survival as well as to the validity of research findings. Consequently, the iterative cycle of action research described above has to be continued until DFM principles are so easy for the business' employees to use that errors in their use are eliminated.

With regard to subject bias, experimental realism and mundane realism are established by the research situation (the normal trading of the business) and research setting (the business premises) being very familiar to the participants (Aronson and Carlsmith, 1986). This prevents subject bias as a result of demand characteristics. Bias due to demand characteristics occurs because the subjects know that they are in an experimental situation in which they are being observed and certain things are expected or demanded of them (Orne, 1962). Also, whilst it is possible that participants may be biased for, or against, the intervention in the short-term, in the longer term, production pressures mean that DFM principles must become routine to enquiry and order processing. Consequently, any initial special effort to make DFM principles successful, or unsuccessful, are overridden by the business' need to rapidly generate correct production information on all occasions.

A disadvantage of using an action research methodology in a business environment is that two other threats to *reliability*, observer error and observer bias, are likely to be increased. The intellectual and physical demands of having to facilitate change as well as observe its effects, are likely to lead to errors. Further, it is difficult to prevent observer bias towards research objectives when it is the observer who must devise the actions which will realise the objectives. In this intervention, the demands placed upon the researcher were significantly reduced by having a person in the business working full-time on carrying out change actions such as cataloguing component characteristics. Also, observation was strengthened by having eight pre-scheduled meetings between Supplier-Y's managing director and an independent researcher to monitor the effects of DFM principles on the business. The records of these meetings provide a systematic, and well documented, audit route to assess the *dependability* of the research (Guba, 1981).

To ensure *construct validity* the measurements of productivity and quality, which are detailed in Chapter 5, were determined and selected prior to application of DFM principles. Measurements were not chosen to fit outcomes (Sidman, 1960).

Proving *internal validity* relies on controlling all the peripheral factors which could affect the dependent variables and, as a consequence, could obscure actual the cause and effect relationships under investigation (in this case, the impact of DFM principles on productivity and quality). In the volatile environment of a medium-sized bespoke manufacturing business serving the UK construction industry, there are many factors which are difficult to isolate and control. Statistical methods of determining causality are of limited effectiveness in this type of research scenario. However, using a negative case analysis approach it is possible to demonstrate research *credibility*. This approach involves the researchers going out of their way to look for negative evidence (Kidder, 1981).

In this intervention, two negative cases were identified: 1. the production information generated by applying DFM principles would have been generated with the same accuracy, consistency and speed anyway, and 2. the improvements to productivity and quality resulting from application of DFM principles would have been achieved anyway.

With regard to design, the affects of applying DFM principles had to be isolated from other methods of preparing production information. This was achieved by embedding standard design rules and standard design metrics into new production planning software. The other methods available for generating production information were the intuitive and experienced-based manual approaches which had been used prior to the intervention. These methods could have generated the same production information, but in the past they had not always been accurate, they had seldom been consistent, and they had never been quick.

With regard to production, this was achieved by using the new production planning software to generate all the production information for selected component types. Also, it is important to note that prior to the intervention there was no awareness that standard design procedures, standard design rules and standard design metrics could be applied to bespoke designs. This was because of several factors. For example, the concept designs produced by the business are not generated internally, they are provided by architects, and it was believed that architects could not have any aspect of design "dictated" to them. Further, it was felt that concept designs were becoming more diverse as clients' expectations for building differentiation were increasing. Also, more and more high performance specialist materials and parts were becoming available for specification by architects. Consequently, production information was far more varied than when fewer, more versatile, materials and parts were used. Perhaps most significantly, training in a bespoke production environment is based on craft demarcation. Therefore, any standardisation of knowledge for general use can be seen by craftspeople as deskilling and as such a threat to their livelihoods. As a result of these factors, the business processed every enquiry and order as if it was entirely unique, and without the intervention would have continued to do so for the foreseeable future.

Threats to the *generalisability* of any single intervention are always significant. Each intervention has its own dynamic and, consequently, it is difficult to move beyond the local causality of the events which lead to the specific outcomes of the particular intervention. Even *transferability* is difficult to establish without multiple interventions. It is recognised that an extensive description of an intervention is required to make further interventions in other settings possible, but without results from any further interventions limited claims for transferability can be made (Denzin, 1989). However, perhaps the most significant benefit of carrying out action research in a business environment is that a successful intervention results in the development of business systems which are readily transferable to similar companies: particularly, if these systems are in the form of computer programs. A drawback is that such systems provide the business which has participated in the research with a competitive advantage which they will not wish to surrender. Nevertheless, successful action research can provide practical guidelines for transfer, together with insights into key technological and organisational barriers.

3.4.4 Testing the research hypothesis: building construction

Chapter 6 describes a single case study conducted between January 1999 and May 2000. The application of DFM principles, took place during a design co-ordination meeting dealing with assisted bathrooms for a healthcare facility. The meeting was held at Contractor-X's site offices. It was attended by a total of ten representatives from the architect, principal contractor, suppliers and sub-contractors. The assisted bathroom construction drawings had already been fully developed for construction.

Assisted bathrooms are contained within bedrooms, and are a fundamental healthcare requirement for the many patients who cannot bathe without the assistance of nursing personnel. The assisted bathroom design details required additional development because of exacting construction and usage requirements.

In order to obtain approval for the trial application of DFM principles, potential support within the construction industry had to be demonstrated to Contractor-X. To address this requirement, three sets of attitude statements relating to the application of DFM principles were developed. Using postal questionnaire, the sample, described above, of two hundred and sixty-seven consultants, manufacturers and assemblers who worked with Contractor-X were asked to indicate the extent to which they agreed or disagreed with the three sets of attitude statements.

Having obtained approval from Contractor-X's Head Office, two preparatory visits were made to the site selected for the trial application. During the second visit, interviews were used to gather opinions about the existing design details from those who had been involved in their design and those who would be involved in their construction.

During the meeting where DFM principles were applied, attendees carried out design evaluations and improvements using DFM principles. Attendees recorded design evaluations, design improvements, and their levels of participation. In addition, structured observation schedules were used by independent non-participants to record the pattern of attendees' involvement. At the end of the meeting, anonymous questionnaires were used to measure attitudes to towards and application of DFM principles. In the months following the meeting, the productivity and quality results of applying DFM principles were monitored. Finally, after results had been gathered, a meeting was held to discuss whether further applications of DFM principles would be beneficial.

Threats to research validity, and tactics to overcome them, were made explicit, before data collection began. Threats to *researcher objectivity* were counteracted by using multiple instruments to gather data from different sources. Interviews; anonymous and open questionnaires; non-participant observation; and analysis of project documentation yielded a variety of quantitative and qualitative data.

Threats to *research confirmability* were counteracted by applying the tenets of quasi-experimentation to the study. Quasi-experimentation includes introduction and manipulation of an independent variable (in this case, DFM principles); the measurement of effects of this manipulation on dependent variables (in this case, the productivity and quality of building construction); and control of all other variables (such as misinterpretation of designs by the operatives constructing them). This clear definition of variables from the outset facilitates assessment of whether study findings flow from study data (Cook and Campbell, 1979).

Threats to *reliability* were of particular significance because the effectiveness of the DFM principles relies on their ability to produce similar results in similar conditions on all occasions. To achieve this, the DFM principles applied were presented in a standard form which is fully explained in Chapter 6. To minimise potential subject error, the form was made easier to follow during several piloting iterations.

Two tactics were used to minimise subject bias. Firstly, purposive sampling was used to select participants who had "preferred" status and had already been awarded the contracts to carry out the work which would be affected by the application of DFM principles. This meant the participants could not gain pre-contractual advantage by showing bias towards the application being successful. Secondly, experimental realism and mundane realism were established by using a situation (design co-ordination meeting) and setting (site office conference room) which were very familiar to the participants (Aronson and Carlsmith, 1986). This was essential to preventing subject bias due demand characteristics (Orne, 1962).

Observer error was minimised through the use of standardised observation schedules and limiting observations periods to no more than one hour. Observer bias was counteracted by using two independent observers and subsequently computing inter-observer agreement. Also, to prevent experimenter expectancy effects, the observers were not provided with an explanation of the experimental hypothesis (Rosenthal and Rubin, 1978). The standard form used provided a systematic, and documented, audit route to assess the *dependability* of the research (Guba, 1981).

To ensure *construct validity* the measurements of construction productivity and quality, which are detailed in Chapter 6, were determined and selected prior to application of DFM principles. Measurements were not chosen to fit the outcome of application (Sidman, 1960). Proving *internal validity* relies on controlling all the peripheral factors which could affect the dependent variables and, as a consequence, could obscure actual the cause and effect relationships under investigation (in this case, the impact of DFM principles on construction productivity and quality). In the fragmented and volatile environment of a large construction project, there are many factors which are difficult to isolate and control.

Statistical methods of determining causality are of limited effectiveness in this type of research scenario. However, using a negative case analysis approach it is possible to demonstrate research *credibility*. This approach involves the researchers going out of their way to look for negative evidence (Kidder, 1981). In this case study two negative cases were identified: 1. the designs generated by applying DFM principles would have been generated anyway, and 2. the improvements to construction productivity and quality resulting from application of DFM principles would have been achieved anyway.

With regard to design, the affects of applying DFM principles had to be isolated from other design activities. This was achieved by the purposive sampling of designs that had already been fully developed for construction. The sampled designs had been developed by an experienced professional team specialising in this type of building. During the design process, they had already sought to eliminate any productivity and quality problems which they had previously encountered. The benefit of sampling these designs was that they provided a challenging application for DFM principles. The drawback was that the potential benefits of applying DFM principles were limited, because the majority of production and quality costs are determined by the end of concept design stage (CIOB, 1992).

With regard to construction, operatives had to be prevented from seeking to improve productivity and quality by improvising design modifications at the workplace. To achieve this, sub-contractors participated in the application of DFM principles and agreed to adhere strictly to the resulting designs.

Threats to the *generalisability* of any single case study are always significant. Each case study has its own dynamic and, consequently, it is difficult to move beyond the local causality of the events which lead to the specific outcomes of the particular case. Even *transferability* is difficult to establish without multiple case studies. It is recognised that an extensive description of a case study is required to make further studies in other settings possible, but without results from any further studies limited claims for transferability can be made (Denzin, 1989). In an attempt to address this problem, participants completed anonymous questionnaires which asked whether they believed that DFM principles could be applied successfully to other buildings. Also, after a "cooling off" period, a review meeting was held to obtain more detailed responses from participants.

3.4.5 Developing and validating strategies for successful DFM application

Chapter 7 describes this stage of the research and provides a full explanation of strategies for successful application of DFM in the construction industry.

Development of the DFM strategy involved creative thinking, and followed several iterations of the cycle now described. *Recognition* that different types of actions were required to apply DFM principles to different types of buildings - *preparation* of a range of different actions which could be carried out to apply DFM principles - *incubation* of these actions in the mind - *illumination* when the creative insights occurred and the DFM strategy was formulated - *verification* when the DFM strategy was developed.

Structured interviews were used to validate the DFM strategy. These interviews involved a purposive sample of seven participants. Two are building designers, two are construction managers, and three are employed by companies which design, manufacture, supply and/or place or install building components. None of these interviewees had previously participated in the research.

This sample comprised representatives of organisations who had being trying without success to implement DFM. They were under direct pressure from a multi-national expert building client to do so, and represented the highest level of understanding of DFM available amongst construction practitioners in the UK.

3.5 Chapter Conclusion

This chapter has discussed research design issues, and it has explained when and why research strategies were selected. These strategies formed the framework for the research methodology which has been described in detail. Threats to research validity and the tactics used to overcome them have been discussed. Samples of the research instruments used are included in the Appendices. A full account of the data gathered by use of these research instruments is provided in subsequent chapters.

4.0 Survey: DFM Application Issues and DFM Success Issues

4.1 Introduction

In this chapter, the findings of further research comprising literature review and field survey are reported. This includes an overview of DFM in the manufacturing industry, and an analysis of issues affecting potential DFM application and DFM success in the construction industry. Further, a research hypothesis is generated and presented.

The field survey comprised two sets of interviews and one postal questionnaire supported by one set of follow-up interviews. As described in section 3.4.2, each set of interviews was carried out with a separate sample of fifteen practitioners, whilst a larger sample of two hundred and sixty-seven practitioners was used for the questionnaire. All of the field survey participants were directly employed by Contractor-X or worked with Contractor-X during building design and/or building construction. Participants were asked to respond on their experiences in the three years leading up to the field survey. The design of the research instruments, and how they were used, is described in detail in appendices B, C, D and E.

4.2 An Overview of DFM

For many manufacturing companies, DFM has become as essential to the product design process, as industrial design and engineering design (Burke and Carlson, 1990). DFM has been applied successfully to many different types of products, including aircraft (Weber, 1994), cars (Kobe, 1992), computers (Digital, 1990) and toys (Kirkland, 1995). Although these products vary considerably in terms of function, aesthetics, ergonomics and technology, they are all standard or custom goods which are the result of producer-led market-specific design. Further, although demand levels for these products vary, they all generate sufficient demand to make the development of product-specific components viable. Figure 4.1 illustrates the relationship of DFM to other elements of the product design process. It indicates

Figure 4.1: Relationship of DFM to other elements of the product design process

Product Imperatives	*Form*	*Function*	*Production*
Design Imperatives	***Industrial design*** *Design to communicate differentiation and function, with simple, safe user interfaces*	***Engineering design*** *Design to deliver greater functionality than is currently available*	***DFM*** ***Design to achieve required product quality at reduced production times and costs***
Design techniques	*Value management* *Quality function deployment*		*Value engineering* *Failure mode effects analysis*

that DFM is an imperative for design engineers who seek to achieve the best available balance between form, function and production. Techniques such as value management and failure mode effects analysis help designers identify design objectives, and quantify these as targets, to be achieved by industrial design, engineering design and DFM.

Figure 4.2 provides an illustrative example of how DFM could be applied to manufactured goods. It indicates the possible stages of a DFM application: it does not present the content of one specific methodology or the record of an actual case. This example is referred to throughout the subsequent description of DFM application issues contained in section 4.3 below.

Figure 4.2: An illustrative example of how DFM can be applied during the design of manufactured goods

	Design Stage	Use of DFM	Design feature	Sample DFM information
1	Evaluate product design	*Enter DFM metrics, which correspond to product features, into Workbook*	*Number of parts:* *original product design comprises 68 parts*	*Metric: Number of parts.* *Original = 68; theoretical minimum no. = 32*
2	Improve product design	*Apply concept design rules and refer to quantified comparisons of materials, processes and/or components*		*Rule: reduce part count and part types, e.g. eliminate parts that act as conduits* *Metric: costs for different manufacturing processes*
3	Evaluate revised product design	*Enter DFM metrics, which correspond to product features, into Workbook*	*Number of parts:* *revised product design comprises 51 parts*	*Metric: Number of parts.* *Revised = 51; theoretical minimum no. = 32*
4	Compare product designs	*Compare values for original product design with the revised product design*		*Value: Design efficiency of original product design = 47%* *Value: Design efficiency of revised product design = 62%*
5	Evaluate initial design of components for revised product	*Enter DFM metrics, which correspond to component features, into Workbook*	*Initially, parts measure 6mm. They are turned through 360°. They can be lifted by one hand, but they severely nest or tangle and they are delicate.*	*Metric: handling time per part = 6.35 seconds* *insertion time per part = 7.50 seconds*
6	Improve initial component design for revised product	*Apply detail design rules and refer to quantified comparisons of materials, processes and/or components*		*Rule: design parts to be self-aligning and self-locating, e.g. provide parts with built in alignment* *Metric: costs for alternative component materials*
7	Evaluate improved component design for revised product	*Enter DFM metrics, which correspond to component features, into Workbook*	*Improved parts still measure 6mm, but they are turned through $\prec$ 360°. Also, they can be grasped and manipulated by one hand easily.*	*Metric: handling time per part = 1.88 seconds* *insertion time per part = 2.50 seconds*
8	Compare component designs for revised product	*Compare values for the initial product redesign with the improved product redesign*		*Value: Assembly time for initial redesign=11.7 mins* *Value: Assembly time for improved redesign = 3.7 mins*

4.3 DFM Application Issues

4.3.1 Introduction

Literature review resulted in the author identifying two key factors which are essential to successful DFM application:

1) standard production design improvement rules (**rules**), and

2) standard production design evaluation metrics (**metrics**).

How these two factors are incorporated into DFM methodologies was investigated, and the field survey was conducted to determine evidence of the applicability of these essential factors to building design and building construction.

4.3.2 The application of DFM design improvement rules

As shown in Stage 4 of Figure 4.2 above, users evaluate the manufacturability of alternative designs by allocating objective values to a range of criteria, such as assembly efficiency. The criteria in different methodologies are often similar (Leaney and Wittenberg, 1992). For example, to work out the assembly efficiency of a design, users identify the theoretical *ideal* minimum number of components by following design rules, such as "test each part's need for existence as a separate component", and identify the *actual* number of components by counting them. Then, they estimate assembly durations for each component from a DFM metrics chart. These durations are entered onto the appropriate DFM worksheet, and individual assembly operation times are added together to give the *ideal*, and the estimated *actual*, assembly times. Assembly efficiency equals *ideal* time divided by estimated *actual* time. As shown in Stages 2 to 4 of Figure 4.2. above, during subsequent design improvement work, efforts are focused on bringing values up to set minimum thresholds, say for example, a design efficiency of 60%. Improvement efforts are guided by design rules, such as, "reduce part count and part types".

In contrast to the widespread use of universal DFM design improvement rules to integrate production best practice into product designs, none of the fifteen construction practitioners who were interviewed about this issue could even offer a definition of what construction best practice is. Their comments included, "best practice is a matter of opinion" and "best practice is just words". Further, they did not cite any written definitions of best practice which are used by designers. Only contractor review of drawings for buildability (CIRIA, 1983), and the building of mock-ups, were recognised as methods of integrating construction best practice into designs by the fifteen interviewees. These responses are particularly noteworthy as the interviewees are all involved in sophisticated building design and building construction work. As detailed in section 3.4.2, all the interviewees have experience of working on individual buildings of over £50 million in value, under a range of traditional and innovative contract forms. Appendix B shows a sample of the interview schedule in which question 1 was used to elicit this information. It also provides a detailed account of how the interviews were carried out.

4.3.3 Application of DFM design evaluation metrics

DFM metrics comprise quantified comparisons of generic material, process and component types presented in illustrated tables, and design evaluation metrics which are presented in charts (Boothroyd and Dewhurst, 1990).

Tables show commonly available materials, processes and components. They compare factors such as, material cost per kilogram, process setup times, and number of fasteners per component. As shown in Stages 2 and 6 of Figure 4.2 above, these illustrated comparisons can be used to speed up selection of materials, processes and components throughout product design. When answering the second interview question, construction industry practitioners cited several sources of information available to help them select components including: compendiums, data sheets and Websites. However, none provide them with quantified comparisons of generic alternatives. Interviewees comments, such as, "I specify what I've used before and hasn't failed", suggest that selection is based on, "habit" as much as "trying to keep abreast of new components as they are brought out". These responses are consistent with findings reported in the literature (Mackinder, 1980).

The evaluation metrics presented in DFM charts indicate standard ratings and/or standard times for different production operations. These operation ratings and/or times indicate how a range of alternative component design features can affect production. In Figure 4.2, Stages 5 to 8, the example, "parts severely nest or tangle but can be grasped and lifted by one hand" is used. Reference to DFM charts indicates that parts which severely nest or tangle take more time to handle and insert than those which do not nest or tangle. Further, the handling and insertion time for parts which severely nest or tangle are shown in comparison to a range of times linked to other common component features. Hence, by making reference to DFM charts, designers can understand the production consequences of choosing one design feature over another.

DFM metrics are similar to work measurement standards developed for job design in the manufacturing industry (Zandin, 1990). Both offer predetermined data developed through experimentation, and both measure precisely defined elementary motions that are consistently repeated in the movement of objects and use of tools. The advantage of DFM metrics is that they enable users to determine production times during concept design, when up to 80% of product quality and cost can be committed (Miles and Swift, 1998). This means informed design changes can be made before they become time consuming and costly. As a result, product development costs and times are reduced because there are fewer late, expensive, design changes due to manufacturing problems (Harding, 1999).

During the second set of interviews, the second sample of fifteen construction industry practitioners were asked how they obtain design evaluation data. Interviewees cited several sources of design evaluation data, most of which were verbal rather than written. For example, approaches such as "ring the Quantity Surveyor." and "talk to the manufacturer" were mentioned on several occasions. Interviewees were also asked how long it takes them to obtain design evaluation information. As shown in Table 4.1 below, interviewees indicated that it often takes up to a day to obtain each piece of information they require. Further, comments such

Table 4.1: Time required to obtain evaluation information

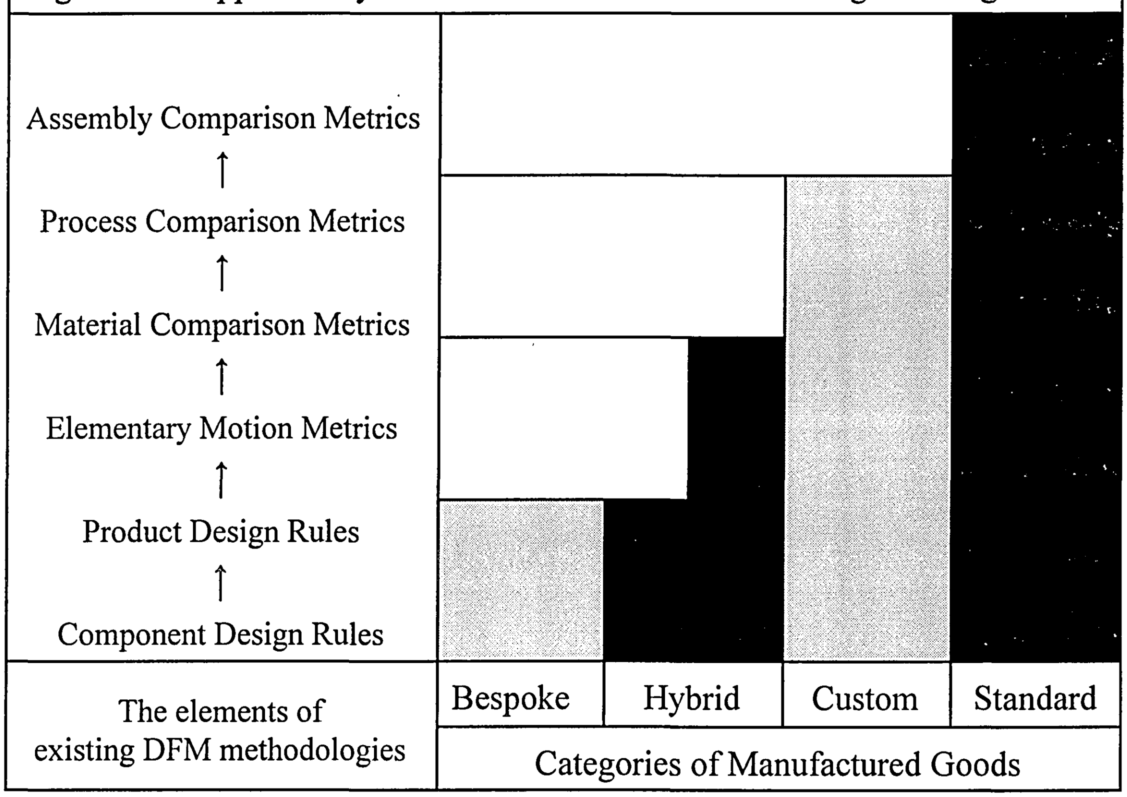
Evaluation information		Up to 59 minutes	1 to 8 hours	1 day or more
Off-site component manufacture	Times			✓
	Costs		✓	
On-site component assembly	Times		✓	
	Costs		✓	

as "price books are not accurate" and "manufacturers' data is gibberish" suggest they have limited confidence in information when they get it. A full account of the second set of interviews is provided in Appendix C.

4.3.4 Discussion of DFM application issues

Figure 4.3 below shows the applicability of the different elements of existing DFM methodologies to different categories of goods. This figure uses the nomenclature introduced in Figure 2.2. and explained in section 2.5.1. Goods are categorised as being bespoke, hybrid, custom or standard depending on their level of pre-order design certainty.

Figure 4.3: Applicability of DFM elements to different categories of goods



Production design rules, such as "reduce part count and part types" are shown to be applicable to all categories of manufactured goods. Such rules do not rely on a high level of design certainty to provide useful guidance, so they can be applied to bespoke goods. In contrast, comparison metrics are only applicable to custom and standard goods For example, assembly comparison metrics are of little use to manufacturers of bespoke assemblies. This is because these manufacturers do not select from common assemblies - they make unique ones. Existing DFM methodologies are easiest to apply to standard and/or custom discrete engineered goods for which specific metrics have been developed. These specific metrics include those for injection-moulded parts, die-cast parts, sheet-metal stampings and printed circuit boards.

It is evident that the application of current DFM methodologies relies on standard DFM design improvement rules and standard DFM design evaluation metrics. Interview responses from the first two samples of fifteen practitioners suggest that these types of universally applicable information are not available within the UK construction industry. As shown by the sample schedules shown in appendices B and C, construction industry practitioners were asked how they integrate best practice into designs; how they select the best available combinations of components and processes; and how they obtain information about potential production times / costs for alternative design options. In response to these questions, no mention was made of rules and metrics, or any equivalents, by any of the interviewees.

4.4 DFM Success Issues

4.4.1 Introduction

Review of DFM literature suggested that there are three design activities which have been essential to DFM success, the design of: mass-produced components to make product assembly simpler; plant to make component manufacture easier; and tooling to make product assembly simpler. These are discussed below. Findings of the field survey designed to determine evidence of these essential factors in the construction industry are also discussed.

4.4.2 The design of components to make product assembly simpler

As shown in Stages 1 to 4 of Figure 4.2 above, DFM initially focuses users' efforts onto the product design as a whole. Firstly, to identify and eliminate components which do not exist for fundamental reasons. This reduces product development times, and cuts production times and costs, without reducing product functionality (Tibbetts, 1995). Secondly, to prevent components being designed which are individually easy to manufacture, but collectively difficult to assemble into a product. Design rules such as, "reduce part count and part types", direct users to think about how overall product designs can be made simpler (McCabe, 1988). Subsequently, when users are designing individual components, they follow rules used for product simplification, as well as other rules such as "use pilot point screws to avoid cross threading" (Sorge, 1994).

Bills of Materials (BoMs) enable DFM users to see the impact of eliminating or modifying a component on all of the other components in a product. As described in Chapter 2, BoMs are developed during product design in the manufacturing industry. They can be used for displaying data inputs and outputs, defining key characteristics of components, and structuring component relationships. Further, BoMs can define interactions between component features (e.g. slots) and characteristics (e.g. tolerances), as well as fix component forms, finishes, configurations and interfaces (Liu and Fischer, 1994).

BoMs provide designers of standard and custom manufactured goods with a universally recognised system of structuring, and rapidly manipulating, product and component design options. This makes it relatively straightforward for design engineers in marketing / assembly companies to explain and agree design changes with their manufacturers.

The lack of BoMs, or an equivalent, in the construction industry makes it difficult to design components so buildings are simpler to construct. However, interviewees made no mention of this problem. They were preoccupied with the difficulties of trying to get buildings, and building components, fully designed in accordance with the deadlines set by construction programmes. This issue was explored in the questionnaire follow-up interviews which are described in detail in Appendix E.

The lack of an equivalent of BoMs in building design makes it extremely difficult for architects and consulting engineers to determine, quickly and confidently, the implications on building construction of eliminating or altering a building's components. Bills of Quantities are used extensively in the construction industry but these do not communicate the interrelationships between components. A review of the contents and use of a Bill of Quantities (Cook, 1991) is now provided.

- Preliminaries

This section of a Bill of Quantities contains *project particulars* relating to personnel, site, contracts and insurance. *Client's requirements* such as tendering, security and safety arrangements are stated. *Contractor's general cost items* are identified. These are items such as management, site accommodation, scaffolding etc. Also, *works by others*, such as statutory bodies are defined.

- Preambles

This section contains details of the specification in terms of the work, the workmanship and materials together with any further information which may qualify the scope and interpretation of work descriptions.

- Measured work

This section contains details of the direct work required to be carried out and describes the components of the final building. There are exceptions to this, such as the excavation and propping of trenches for foundations. Each item of work is listed separately and consists of a description, unit of measurement and quantity with spaces to the side for tenderers to insert theirs unit rates and total prices. The items are often grouped into work sections such as masonry, surfaces finishes, electrical supply/power lighting systems. An alternative to this is the elemental format where the superstructure of a building is split into major elements such as upper floors, roof, stairs, external walls, windows and external doors. However, within each element the order of items follows work sequence. Often there is ambiguity in the requirements of measured work items. Consequently, before pricing items reference must be made to the preambles.

- Prime Cost

Prime cost relates to work which is to be carried out by sub-contractors or suppliers selected by the architect. This can include the installation of lifts, erection of structural steelwork, fixing of suspended ceilings, installation of electrical services etc, and/or supply of components such as door ironmongery.

- Provisional sums

Provisional sums are the term used to describe money allocated for carrying out work which cannot be fully defined. For example, where the extent of repairs to existing stone jambs and cills is difficult to ascertain it could become a provisional sum. Further, items may be marked Approximate Quantity (provisional) in the measured work section. This indicates that the descriptions and/or quantities may be altered later.

- Dayworks

Dayworks are the method by which contractors are paid for carrying out all the additional work ordered by the architect during the contract. The Bill of Quantities contains notional monies for labour, materials and plant. Under each of these three work categories there is a provision for the contractor to insert a percentage addition.

- Contingency

This is an amount of money inserted into the Bill of Quantities by the architect to be used by him as considered necessary. Such sums are usually expended on work which is either unforeseen or unaccounted for. The sum is therefore generally used as a buffer to offset some affects of cost escalation.

The foregoing review of the contents of a Bill of Quantities explains how it provides an approximate measurement of the labour, plant and components necessary to construct a building. Its purpose is to facilitate competitive pricing by alternative contractors. It does not provide certain definition of the forms, finishes, configurations and interfaces of a building's components.

Although Bills of Quantities are widely used, field survey interviewees made most comment about drawings. They considered fixing the design of a building to be an increasingly protracted process in which "drawings are only a guide" because, "designers lack practical experience". This process relies on frequent meetings to "sort out" designs. Also, there was a common opinion that once building design had been fixed, it was seldom repeated. Notably, an interviewee working on a supermarket chain's build programme stated that, "every store is different". Further, interviewees suggested that information is often contradictory and usually changes during building construction. Criticisms included, "not properly co-ordinated", "issued at the last minute" and "not definitive".

4.4.3 Design of component-specific plant and product-specific tooling

DFM methodologies often direct users how to achieve minimal cost component manufacture from existing resources, and may direct future investment in more efficient combinations of processes and materials. Following DFM rules such as, "design multi-functional parts", manufacturers consolidate parts into assemblies (Colucci, 1994). This reduction of component numbers results in cuts to indirect costs incurred during procurement, inventory control etc.

When consolidating several parts into one, manufacturers often invest in near net shape processes (e.g. casting, moulding etc.). These processes are far more efficient than subtractive manufacturing processes (e.g. cutting, drilling etc.), and result in radically reduced direct manufacturing costs. Also, assembly productivity and quality are improved because there are fewer components, and consequently fewer interfaces, per product (Branan, 1991). This type of manufacturing investment in component-specific plant is economically viable when components are to be mass-produced.

DFM methodologies cover: manual, automatic, and robotic assembly. Rules exist such as, "minimise the need for reorientations during assembly", encourage the simultaneous design of components and assembly tooling. This can result in tooling which always grasps and positions components right first time (Beddis, 1989).

The field survey questionnaire was designed to determine evidence of the design of plant to make building component manufacture easier and the design of tooling to make building construction simpler. In question 3.3., respondents were asked to indicate which types of organisations, if any, they had collaborated with in the introduction of new components and services. Full details of the questionnaire are provided in Appendix D.

As shown in Table 4.2 below, most respondents had collaborated with other organisations, but manufacturing companies, assembly companies, and plant companies had seldom collaborated with each other.

Table 4.2: Design collaborations between organisations

Manufacturers' design collaborations			Assemblers' design collaborations		
Type of organisation		%	Type of organisation		%
1	Design consultants	37.1	1	Construction consultants	30.2
2	Construction consultants	29.5	2	Building design consultants	27.0
3	Material processing companies	11.9	3	Material processing companies	16.7
4	Other component manufacturers	6.4	4	Component manufacturers	10.0
5	Cost consultants	5.2	5	Cost consultants	6.7
6	Component assemblers	3.2	6	Building plant companies	3.6
7	Building plant companies	0.0	7	Other component assemblers	1.8
No design collaborations		6.7	No design collaborations		14.0

Responses were received from twenty-five manufacturers and sixty-nine assemblers. Over two thirds of their design collaborations were with consultants, but less than one twentieth of their design collaborations were with plant companies. As ninety percent of these manufacturers and assemblers indicated that they have their own design equipment and design personnel, their lack of collaboration with plant companies is unlikely to be due to lack of design activity. Table 4.2 was generated using the Summarise Frequencies function of the Statistical Package for the Social Sciences (SPSS). A detailed description of the analysis of responses is contained in Appendix D.

During questionnaire follow-up interviews with fifteen construction industry practitioners, manufacturers and assemblers had a common view that they collaborated mainly with consultants, because, “they control what we do”. However, the consultants who were interviewed suggested that they had little control over either manufacture or assembly. Opinions included, “manufacturers will only develop a part for a very big building”, and “I’m not sure interfaces will work until they are built”. A sample of the schedule used for follow-up interviews is contained in Appendix E.

The questionnaire also asked manufacturers, assemblers and consultants to indicate the extent to which they agreed or disagreed with three attitude statements, concerning potential barriers to design collaborations, according to an ordinal scale (5 = strongly agree, 1 = strongly disagree). Table 4.3 below shows the rank scoring of the 127 responses which were received.

Table 4.3: Barriers to design collaboration	
Rank	Barrier
1	Communication between organisations
= 2	Current approaches to building procurement
= 2	Lack of building standardisation

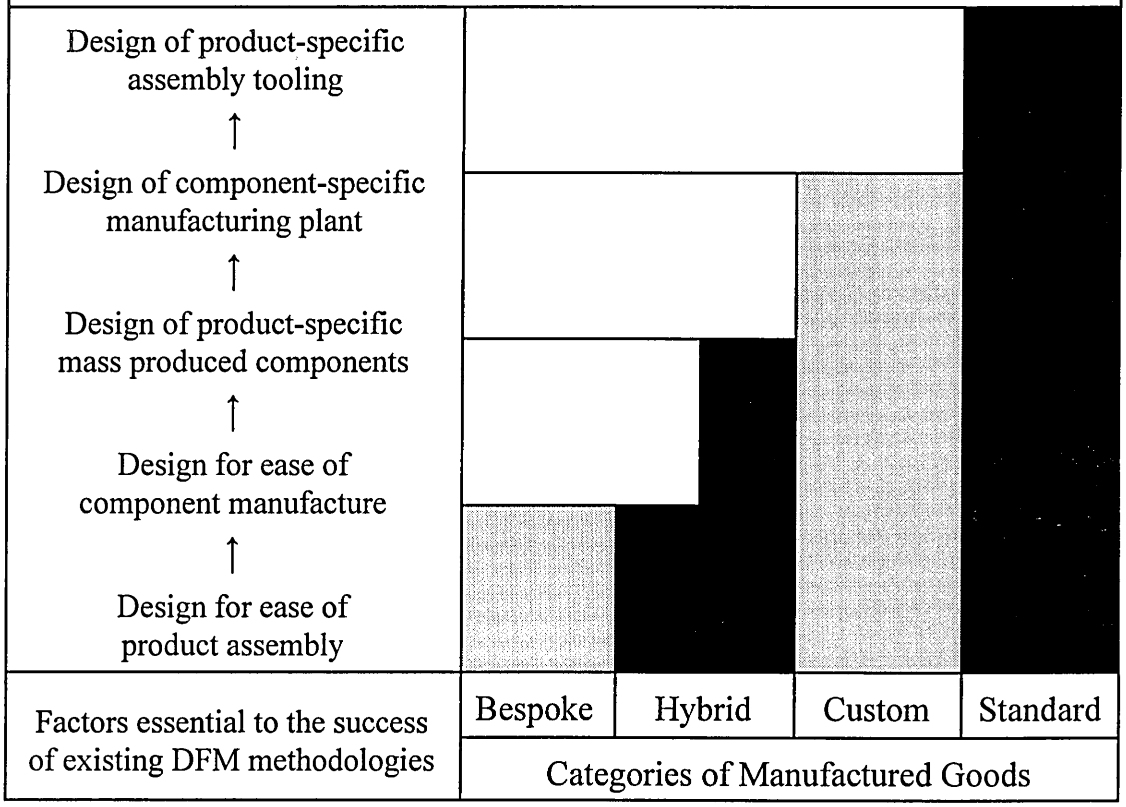
Communication problems were identified by respondents as the primary obstacle to designing in collaboration with other organisations. Current approaches to procurement, and lack of standardisation, were identified as equally important secondary barriers. All three statements received agreement or strong agreement. Using SPSS, responses were analysed according to the Kruskal-Wallis 1-Way test in order to obtain a preliminary ranking scale of importance. Responses were then rank scored to provide an indication of significant differences by applying the Mann-Whitney U-Wilcoxon Rank Sum W test. Further, actual responses were related to the median response by carrying out the Wilcoxon Matched-Pairs Signed-Ranks test. Further, details of the analyses carried out are provided in Appendix D and Appendix F.

Subsequently, during questionnaire follow-up interviews, several practitioners emphasised the opinion that individual organisations "don't think about the implications of their actions outside their own envelope". However, even internal collaborations (i.e. inside "their own envelope") between design and production functions may be limited, as only twenty-four percent of the manufacturers who responded to the questionnaire indicated that they had designed products and related processes at the same time within their own companies.

4.4.4 Discussion of DFM success issues

Figure 4.4 below shows the factors which have been essential to the success of existing DFM methodologies. As with Figure 4.3 above, goods are categorised by their level of pre-order design certainty.

Figure 4.4: Factors which have been essential to DFM success



This figure suggests that when goods are standard, it is both feasible and viable to develop mass-produced product-specific components, component-specific manufacturing plant and product-specific assembly tooling using DFM. In contrast, when goods are bespoke these design activities are not feasible and viable. Nevertheless, these types of one-off goods may still benefit from the application of rules which direct designers towards better consideration of ease of product assembly and ease of component manufacture.

However, the remarkable success of current DFM methodologies relies on assembly companies, working with manufacturing companies and plant companies to develop mass produced product-specific components, component-specific manufacturing plant and product-specific assembly tooling. This results in components that are easier to manufacture, and simpler to assembly into products, which, in turn, leads to higher productivity and fewer quality problems.

The lack of BoMs, or an equivalent, in the construction industry makes designing components to simplify building construction extremely challenging. This is because it is difficult for an architect to see the implications of eliminating or modifying a component on the overall building design. For example, if a building designer is considering whether to use a steel frame instead of a concrete frame for a large bespoke building, s/he will not be able to foresee how the need to fix fire insulation boards to the steel frame will affect the form of every wall to ceiling interface. The building designer will rely on the building contractor to achieve ad-hoc solutions at site to any problems which may arise as a result of the design decision (Ferguson, 1989).

Responses to section 3 of the questionnaire suggest that there is very little collaboration between manufacturing, assembly and plant companies in the UK construction industry. This is demonstrated by 35% of respondent assemblers indicating that they had no experience of new components which make it easier for them to carry out their work; and over half of assemblers indicating that they had not been able to reduce their lead times, or the time which they required to fulfil an order. Further, as shown in Table 4.4, which was generated using SPSS, seventeen percent of respondent assemblers had increased their lead times in the three years leading up to the questionnaire. These findings suggest that there is a need for more design collaboration amongst manufacturing, assembly and plant companies to increase construction industry performance.

Table 4.4: Time performance of assemblers			
Changes to time performance in previous 3 years		Lead time	Order time
Percentage of assemblers offering:	reduced time	30.4%	44.6%
	unchanged time	52.2%	47.7%
	increased time	17.4%	7.7%

The need for manufacturers and assemblers to work together has been widely recognised (Brookes and Stacy, 1991; Gray, 1996). However, attitude statement responses and interviewees' comments suggest that there are organisational barriers to achieving this.

4.5 The Limitations of Existing DFM Methodologies

4.5.1 DFM application

It has been explained above that existing DFM methodologies are most easily applied to standard and custom goods comprising components for which DFM metrics have been specifically developed. Also, it has been argued that, whilst DFM design rules may be applied during the design of many manufactured goods, DFM comparison metrics can only be applied during the design of manufactured goods containing some common materials, processes and assemblies.

In Chapter 2, it was argued that the format of design information is determined more by design leadership and design reuse than the industry in which design takes place. Also, it was suggested that there is no fundamental reason why the types of design information prevalent in the design of standard and custom manufactured goods could not be prevalent in the design of standard and custom buildings. That is provided there is sufficient repetition of pre-order design certainty to make investment in building-specific information systems feasible and viable.

This suggests that there is no fundamental reason why standard production design improvement rules, and standard production design evaluation metrics cannot be applied to standard and custom buildings. As discussed in Chapter 2, existing DFM methodologies have already been applied to standard building components.

However, existing DFM methodologies were not developed for buildings, so their rules and metrics are not necessarily directly applicable to buildings. As a consequence, it is likely that whilst some design rules may be useful because of their universal nature, design metrics are likely to be less useful because they have been developed for elementary manufacturing motions and common manufacturing materials, processes and assemblies.

Figure 4.5, below, illustrates the potential applicability of existing DFM methodologies to standard buildings. Figure 4.5 uses the example provided in

Figure 4.5: Applicability of existing DFM methodologies to standard buildings

	Component levels		Building example
Some DFM Rules & Some DFM Metrics	0	Product	*Self-contained portable office*
	1	Assembly	*External door set for portable office*
	2	Sub-assembly	*Door set frame*
	3	Part	*Door frame jamb*
	4	Material	*Aluminium used to manufacture jamb*

Chapter 2 of a self-contained portable office, and shows some of the different components which might be used in its construction. These types of buildings tend to be fabricated in factories. Consequently, DFM procedures, rules and metrics are far more applicable to these types of buildings than bespoke buildings that are constructed from loose materials and parts at site.

Figure 4.6 illustrates the potential applicability of existing DFM methodologies to bespoke buildings. It uses the example provided in Chapter 2 of an office building with a curved entrance, and shows some of the different components which might be used in its construction.

Figure 4.6: Applicability of existing DFM methodologies to bespoke buildings

DFM elements	Component levels		Bespoke building example
Some DFM Product Design Rules & Some DFM Component Design Rules	0	Product	*Office with curved entrance*
	1	Assembly	*Reception area*
	2	Sub-assembly	*Ceiling*
	3	Parts	*Metal interlocking ceiling tiles*
	3	Formed material	*Plasterboard*
	3	Formless material	*Plaster and paint*

Figure 4.7 below illustrates the potential applicability of existing DFM methodologies to bespoke building components. It uses the example provided in Chapter 2 of a curved reception desk, and shows some of the different parts and materials which might be used in its manufacture.

Figure 4.7: Applicability of existing DFM methodologies to bespoke components

	Component levels		Bespoke component example
Some DFM Rules & Some DFM Metrics	0	Product	*Curved reception desk*
	1	Assembly	*Curved base structure*
	2	Sub-assembly	*Curved drawer unit*
	3	Parts	*Curved metal brackets*
	3	Formed material	*MDF; veneers*
	3	Formless material	*Adhesive; lacquer*

As DFM metrics have been developed to communicate the affect of design options on manufacturing operations, it is possible that some of these metrics could be applied usefully to the design of some bespoke building components. Designers of discrete engineered assemblies, such as bespoke ventilation plant, would be most likely to find metrics in existing methodologies relevant.

4.5.2 DFM success

It has been explained above that the remarkable success of current DFM methodologies relies on assembly companies, working with manufacturing companies and plant companies to design mass produced product-specific components, component-specific manufacturing plant and product-specific assembly tooling. This results in components that are easier to manufacture, and simpler to assembly into products, which, in turn, leads to higher productivity and fewer quality problems. As discussed in Chapter 2, these types of design activities are often feasible and viable for standard and custom goods such as printers and cars. For bespoke and hybrid goods such as ships, these types of design activities are less feasible and viable. This means that designers of bespoke and hybrid goods cannot always apply rules concerning simplification of assembly and ease of manufacture with the same success as designers of standard and custom goods.

Figure 4.8 illustrates the DFM success factors which are feasible and viable for standard buildings. As explained in Chapter 2, the design of standard buildings, like

<table>
<tr><th colspan="4">Figure 4.8: DFM success factors which are feasible and viable for standard buildings</th></tr>
<tr><td rowspan="6">Design for ease of building construction
&
Design for ease of component manufacture
&
Design of product-specific mass produced components
&
Design of component-specific manufacturing plant
&
Design of product-specific assembly tooling</td><td colspan="2">Component levels</td><td>Building example</td></tr>
<tr><td>0</td><td>Product</td><td>Self-contained portable office</td></tr>
<tr><td>1</td><td>Assembly</td><td>External door set for portable office</td></tr>
<tr><td>2</td><td>Sub-assembly</td><td>Door set frame</td></tr>
<tr><td>3</td><td>Part</td><td>Door frame jamb</td></tr>
<tr><td>4</td><td>Material</td><td>Aluminium used to manufacture jamb</td></tr>
</table>

the design of standard manufactured goods, is producer-led and market-specific. This makes development of product-specific mass produced components, component-specific manufacturing plant, and product-specific assembly tooling technically feasible and economically viable. Standard buildings include: self-contained portable buildings; kit form housing; and modular building systems. In addition to these, there are custom buildings designed for repeated construction for one client, such as McDonald's drive-thru restaurants. Although it is unlikely that these types of buildings will ever comprise the majority of commercial construction work (Gray, 1996) they are nevertheless a requirement for many of the industry's clients. Also, many large house builders offer a range of custom house types, and housing currently comprises a quarter of all construction output (DETR, 1999b).

Figure 4.9 illustrates the DFM success factors which are feasible and viable for bespoke buildings. These are far more limited than those for standard buildings. They are likely to be restricted to achieving productivity and quality improvements by better use of mass-produced general purpose building materials and parts, one-off sub-assemblies and assemblies, general purpose plant and general purpose tooling.

Figure 4.9: DFM success factors which are feasible and viable for bespoke buildings

DFM elements	Component levels		Bespoke building example
Design for ease of building construction & Design for ease of component manufacture	0	Product	*Office with curved entrance*
	1	Assembly	*Reception area*
	2	Sub-assembly	*Ceiling*
	3	Parts	*Metal interlocking ceiling tiles*
	3	Formed material	*Plasterboard*
	3	Formless material	*Plaster and paint*

As shown in Figure 4.10 below, the DFM success factors which are feasible and viable for bespoke building components are similarly limited because of reliance on general purpose plant and tooling.

Figure 4.10: DFM success factors which are feasible and viable for bespoke components

	Component levels		Bespoke component example
Design for ease of component assembly & Design for ease of component manufacture	0	Product	*Curved reception desk*
	1	Assembly	*Curved base structure*
	2	Sub-assembly	*Curved drawer unit*
	3	Parts	*Curved metal brackets*
	3	Formed material	*MDF; veneers*
	3	Formless material	*Adhesive; lacquer*

In contrast, the design of mass produced standard building <u>components</u> could include the development of component-specific manufacturing plant. Success, however, would be limited if components were not building-specific, as they would not necessarily make buildings simpler to construct. As discussed above, rules contained in existing DFM methodologies are initially focused on assembly simplification.

4.5.3 Opportunities for successfully applying existing DFM methodologies

As discussed above and summarised in Figure 4.11 below, opportunities for successfully applying existing DFM methodologies to buildings and building components are limited.

Figure 4.11: Opportunities for successful application of existing DFM methodologies

Categories		Application	Success
Buildings	Standard / custom	?	?
	Bespoke / hybrid	✗	✗
Building components	Standard / custom	✓	?
	Bespoke / hybrid	✗	✗

The analysis of literature review and field survey results reported in this chapter suggests that it may be possible to successfully apply existing methodologies to standard and custom buildings where their production involves factory pre-fabrication. Further, as reported in section 2.4.3, an existing DFM methodology has been applied during the design of electric shower heater units which are designed and manufactured by Caradon. However, although this improved component manufacture, it has not necessarily improved construction productivity and quality for specific buildings.

Having determined that opportunities for successful application of existing DFM methodologies are limited, the analysis of inductive research findings focused on the potential for successful application of DFM principles. As described in the next section, this resulted in the generation of the research hypothesis.

4.6 Generation of the Research Hypothesis

McNeill (1995) describes an hypothesis as an intelligent guess, based on research, in a form that can be tested. In this research, the "intelligent guess" was generated during the analysis of DFM principles, and opportunities for their potential application, which is described below

4.6.1 DFM principles

The foregoing analysis identified standard production design improvement rules and standard production design evaluation metrics as being the two fundamental principles of DFM. Figure 4.12 provides an indication of their relative cost.

Figure 4.12: Examples of different levels of design metrics

DFM principles		Cost
Standard production design evaluation metrics	Elementary motion metrics	*High*
	Assembly comparison metrics	
	Process comparison metrics	↕
	Material comparison metrics	
Standard production design improvement rules	Product rules	*Low*
	Component rules	

Component design improvement rules, such as "use pilot point screws to avoid cross threading" can be developed easily, and can be applied to bespoke and standard goods. In contrast, assembly comparison metrics are more costly to develop and have a far more limited application. For example, assembly comparison metrics include: part data such as the total number of parts, the number of unique parts, number of fasteners; and time data such as slowest part, fastest part, and total assembly time. These measurements are of limited usefulness when the forms, finishes, configurations and interfaces of assemblies are always uncertain until production is complete. Consequently, assembly comparision metrics are of limited usefulness in the design of bespoke goods. Product design improvement rules, such as "reduce part count and part types" can be developed as easily as component design improvement rules. However, they are more difficult to apply because product design changes are more far reaching. As discussed above, it is difficult for designers to see the overall affect on a product of eliminating or modifying its components.

Like comparison metrics, elementary motion metrics, such as handling time per part and insertion time per part, are costly to develop, but because of their elementary nature they are more widely applicable. However, they are not as effective as comparison metrics because they have to be aggregated to inform designers of the consequences of their decisions. For example, an assembly comparison metric states what the assembly time is. If motion metrics are used, times have to be looked up for every assembly motion and then added together.

4.6.2 Opportunities for successful application of DFM principles

Standard production design improvement rules and standard production design evaluation rules are the two fundamental principles of DFM, but they are not tied to DFM. Standard rules and metrics can be developed for buildings just as they have been for manufactured goods. As discussed above, DFM rules and metrics have different levels of applicability and success in the manufacturing industry, depending to what extent goods are standard or bespoke. Although buildings are more often bespoke than standard this does not prevent application or success. Opportunities for emulating the remarkable productivity and quality improvements achieved in the manufacturing industry as a result of DFM application may be limited to standard and custom building. However, as discussed in Chapter 2, even if only some of these improvements can be transferred to bespoke and hybrid buildings they will still be significant.

4.6.3 The research hypothesis

Figure 4.13 below summarises the potential opportunities for successful application of DFM principles. It shows that standard production design improvement rules can be applied to all buildings and building components. These rules may include exact DFM rules, modified DFM rules and new standard production design improvement rules developed for buildings and building components.

Figure 4.13: Potential opportunities for successful application of DFM principles

Design categories		Standard production design improvement rules	Standard production design evaluation metrics
Buildings	Standard / custom	✓	✓
	Bespoke / hybrid	✓	?
Building components	Standard / custom	✓	✓
	Bespoke / hybrid	✓	?

Without BoMs, or an equivalent, there will be difficulties in applying product design rules with speed and confidence. However, BoMs are already feasible and viable for standard buildings and, with developments in computer technology, may eventually be possible for other categories of buildings (Brister, 1995).

As discussed above, standard production design evaluation metrics are costly to develop. Further, it is unlikely that existing DFM metrics can be widely applied to buildings. However, neither of these problems prevent development of metrics. Although, as shown in Figure 4.13, their potential for successful application to bespoke buildings and bespoke building components is less certain than their potential for successful application to standard buildings and standard building components.

To use McNeil's analogy, Figure 4.13 represents the "intelligent guess" resulting from inductive research. Consideration of how to encapsulate this succinctly as a statement "that can be tested" resulted in the generation of the research hypothesis:

DFM principles can be applied successfully to building components and buildings.

Action research and a case study were carried out to test this research hypothesis, and are reported in the next two chapters.

4.7 Chapter Conclusion

In this chapter, the findings of inductive research comprising literature review and field survey have been reported and discussed. An overview of DFM has been provided. Issues affecting DFM application and DFM success have been investigated. It has been concluded that the factors which have enabled the successful application of existing DFM methodologies to standard and custom manufactured goods, are seldom found in the design and production of bespoke and hybrid buildings. It has been argued, that in spite of these difficulties, the fundamental principles of DFM can be applied to all buildings and building components. Finally, the research hypothesis was generated.

5.0 Study I: Applying DFM Principles to Building Components

5.1 Introduction

This chapter describes an action research intervention designed to determine whether DFM principles can be successfully applied to building components. An overview of the research setting and the research method which was used is provided. Component design in the construction industry is compared with how DFM is used in the manufacturing industry during component design to improve productivity and quality. Each stage of the intervention is described in detail and the results of the intervention are reported. Issues affecting the use of building component design to improve building construction are discussed.

5.2 Research Overview

5.2.1 The research setting

The intervention took place within Supplier-Y, a business which manufactures and installs bespoke building components in the UK construction industry. As explained in Chapter 2, building components producers can be grouped into two categories. Those which design, manufacture and supply standard and custom materials and parts, and those which offer the capability to manufacture, supply and install bespoke sub-assemblies and assemblies.

Examples of standard materials and parts include: bricks, plasterboard, cement, plaster, drainage pipes, and heating pipes. Examples of custom materials and parts include: raised floor tile systems, suspended ceiling systems, and paint systems. Both standard and custom materials and parts tend to be produced for stock.

Businesses that supply standard and custom materials and parts are often large and can be multinationals, such as the Hanson Group. In contrast, businesses such as Supplier-Y offer the capability to produce bespoke sub-assemblies and assemblies on a one-off basis. These businesses tend to operate regionally, buying in the standard materials and parts which are produced by much larger companies. Examples of sub-assemblies include steel staircases with hardwood treads, and glazed screens with sign written glass. Examples of assemblies include prefabricated clean rooms and prefabricated hotel bedrooms. These sub-assemblies and assemblies may often have common features but they are produced to order not for stock.

During the period of the research, Supplier-Y manufactured a wide range of building components including:

- service and storage furniture, such as counters, desks, workstations;
- washroom interior fittings, such as cubicles, duct panels, vanity units; and
- partitioning fixtures, such as doorsets, screens, and wall panels.

Supplier-Y manufactures with a diverse range of materials such as: natural timber, synthetic stone, plastic laminates, and metal extrusions. The company has three factories on one site in southern England. It had a financial turnover of approximately £5 million in 1999.

Out of a total work force of approximately seventy people, some thirty skilled and semi-skilled production operatives are employed in the three factories. They use a wide range of general purpose manufacturing plant to cut, drill, join and finish materials. The business does <u>not</u> carry out any casting or forming manufacturing operations, such as injection moulding and extruding. Project and job, rather than batch and line, manufacturing processes are used. Supplier-Y had invested over £1.5 million in new premises, up-to-date plant and employee training during the three years prior to the intervention.

Supplier-Y employs approximately twenty skilled operatives to install the components which it manufactures. Installation is carried out at building sites using general purpose powered and non-powered hand tools. Larger items of plant, such as scaffold towers, are obtained by short-term hire contract when necessary. Site power and welfare facilities, such as toilets, are provided by the principal contractor, not by Supplier-Y. Installation is labour intensive work, with operatives having to carry components from outside to their fixing locations inside the building under construction. Components are often bulky and heavy.

In addition to the direct production personnel working in the factories and at site there are approximately fifteen employees involved in indirect production activities, such as preparing production information, supervising production and monitoring production quality. Prior to the intervention, production information was either prepared manually, either with pen and paper, or with the aid of general purpose word processing and spreadsheet computer software. This limited use of IT is commonplace amongst such organisations (Dawood, 2000).

Supplier-Y does not generate the concept designs for the components which it manufactures and installs. Concept drawings for components are prepared by architects or interior designers on behalf of clients. Supplier-Y tenders to secure one-off contracts to manufacture and install these components. Although the business does not generate concept designs, it often prepares production drawings and always has the opportunity to offer advice about how concept designs could be modified for ease of manufacture and/or installation. However, prior to the intervention, Supplier-Y did not have a formal design method, for use during the preparation of production information, to improve the productivity and quality of component manufacture and installation. Further, there was no knowledge of DFM in the business. The business did not improve concept designs to facilitate use of the best available production technology. Instead, general purpose production resources were reconfigured in response to every concept drawing received. Each day, operatives and plant were deployed in different arrangements to suit the particular production requirements of specific component designs. This approach reflected the craft origins of the business and, in spite of its limitations, Supplier-Y regularly completed orders from many of the industry's leading construction management companies, including Laing, McAlpine and Tarmac. Also, the price and quality of Supplier-Y's work was sufficiently competitive for orders to be received from a number of prestigious property development companies. The type of customers won and retained by Supplier-Y suggests that its management of design and production was equal to, or better than, that of its competitors.

5.2.2 The research design

An action research methodology was used to apply and evaluate DFM principles within Supplier-Y from June 1998 to September 2000. Research focused on bespoke components, because, as explained in Chapter 4, that is the most challenging application for an approach most commonly applied to standard goods.

During the period of the action research the author was employed within Supplier-Y to formulate business development strategies and oversee their implementation. An action research methodology was required because introducing standard DFM principles into the operating systems of a bespoke manufacturing business involves significant technological and organisational change. Action research methodologies add the achievement of change to the more conventional research goals of describing, understanding and explaining. An iterative cycle of *planning*, *acting*, *observing* and *reflecting* is continued until the relevant processes in the organisation have been improved; the people in the organisation understand the processes; and the organisational environment in which the processes take place have been improved.

Measuring the benefits of process improvements is necessary to evaluate the success of action research. However, measurements which are often available to researchers investigating the production of standard and/or custom goods are not always relevant to bespoke production. For example, the number of cars produced per operative per annum is a common measure of assembly plant productivity in the automotive industry. Supplier-Y does not gather this type of product-specific performance data. However, this is because of the nature of the company's outputs, not because of a lack of will to measure performance. As explained in Chapter 2, bespoke building components have many and uncertain form, finish, configuration and interface options. This results in the use of general purpose production processes, plant and tooling, and it also results in the use of general measures of business performance. Just as it is neither feasible nor viable for Supplier-Y to develop product-specific mass-produced components and product-specific assembly tooling, it is neither feasible nor viable for them to develop product-specific performance measurements. Supplier-Y cannot measure the number of a particular component produced per operative per annum because Supplier-Y does not produce the same components repeatedly.

Similarly, the measurement of tool change over times have little relevance to Supplier-Y. This is because the company uses general purpose plant and has no input into the design of that plant or its tooling and, as a consequence, can do little to drive down change over times. Also, general purpose plant often has only one tooling option. For example, a dimension saw has a saw blade which is only changed when it is blunt, it is not changed for other tooling options.

Measurements of quality which are commonly applied to standard and custom goods also have limited relevance to Supplier-Y. This is because in the production of bespoke goods, the definition of quality is customer-led and, as a result, quality criteria are uncertain. For a business which produces standard and custom goods, the situation is very different: the definition of quality is producer-led and quality criteria are certain. For example, it was reported in Chapter 2, that Toyota have cut defects by two thirds (Madigan, 1997), however, Toyota define quality criteria for the high repetition of standard assembly options which it designs. In simple terms, Toyota are certain what quality criteria they are trying to fulfil, and Supplier-Y are uncertain what the quality criteria will be from one order to the next. Particularly, as the identification of defects by customers can allow them to withhold payment from companies such as Supplier-Y. This can lead to a situation where defects are said to exist by property developers until they have rented out a building which they have had constructed. Then when tenants are found, the "defects" are no longer mentioned and payments are released.

Another difficulty arising from customer-led design is that, without standard components to design quality into, the introduction of statistical process control techniques is very difficult. Indeed, at Supplier-Y continual visual inspections are carried out. This is because the properties of natural materials which are selected by customers, such as hardwood veneers, have a high level of variation compared to synthetic materials. Consequently, successful selection and batching depends on visual inspection, rather than quality assurance by vendors or random sampling during receipt. Furthermore, the combination of customers' aesthetic and functional requirements often results in demand for components incorporating both natural and synthetic materials. These can have very different performance characteristics which have to be monitored by repeated in-process inspections during manufacture.

The problems of measuring the productivity and quality of bespoke production have resulted in Supplier-Y using general measurements of performance. These provide the company's directors with an indication of whether the business is making or losing money and whether or not they need to take action.

Although the use of general performance measurements has proved effective for Supplier-Y's directors, the lack of more detailed measurements makes it difficult to apply a quasi-experimental research design. In this intervention, the independent variable was DFM principles and the dependent variables were the productivity and quality of building component production. To evaluate the affect of the independent variable on the dependent variables it is necessary to take pre- and post-intervention measurements of productivity and quality. If the intervention had been carried out in a company which produces standard and custom goods, measurements such as tooling change over times, products per operative per annum could have been available or could have been requested.

However, as discussed above, for Supplier-Y these types of measurements were not particularly relevant, and the company's directors were therefore unreceptive to suggestions that attempts should be made to apply them. As a consequence, the general measures available had to be used. These are non-productive costs and financial turnover. Supplier-Y measures non-productive costs as a proportion of annual financial turnover. These costs comprise:

- personnel employed to prepare production information;
- overtime paid to operatives due to the late issue of production information;
- personnel employed to supervise production;
- personnel employed to monitor production quality; and
- overtime working as a result of quality problems.

Financial turnover was seen as an important measurement by Supplier-Y because prior to the intervention, increases in orders had always resulted in the need for additional personnel to prepare production information. This, in turn, had resulted in the need for more office space. As Supplier-Y has no more space available for development at its current location, finding a way to increase financial turnover without increasing personnel was essential for the company's growth.

5.3 Comparing Design for Manufacture with Manufacturing a Design

5.3.1 Design for manufacture

As explained in Chapter 2, building designers have less control over the forms and finishes, configurations and interfaces of components than design engineers working for marketing / assembly companies in the manufacturing industry. This is because building design is often customer-led and location-specific. Architects' control of the design of each building is constrained by factors such as clients' and town planners' instructions, site features, and, in the case of refurbishments, the fabric of the existing building. As a result, it is seldom feasible and viable for building component manufacturers to collaborate with architects in the development of mass produced, building-specific, sub-assemblies and assemblies (Morton and Jagger, 1995). As explained in Chapter 2, building component manufacturers tend to offer either a range of mass produced, standard materials and parts, or the capability to produce one-off bespoke sub-assemblies and assemblies. Architects' influence over the design of mass produced, standard materials and parts often being limited to participation in manufacturers' market research.

Figure 5.1 below contrasts the architects' control of building designs with design engineers's control of product designs. It indicates that architects have more control over the design of bespoke building components than standard building components. This means that opportunities to "design multi-functional parts" are

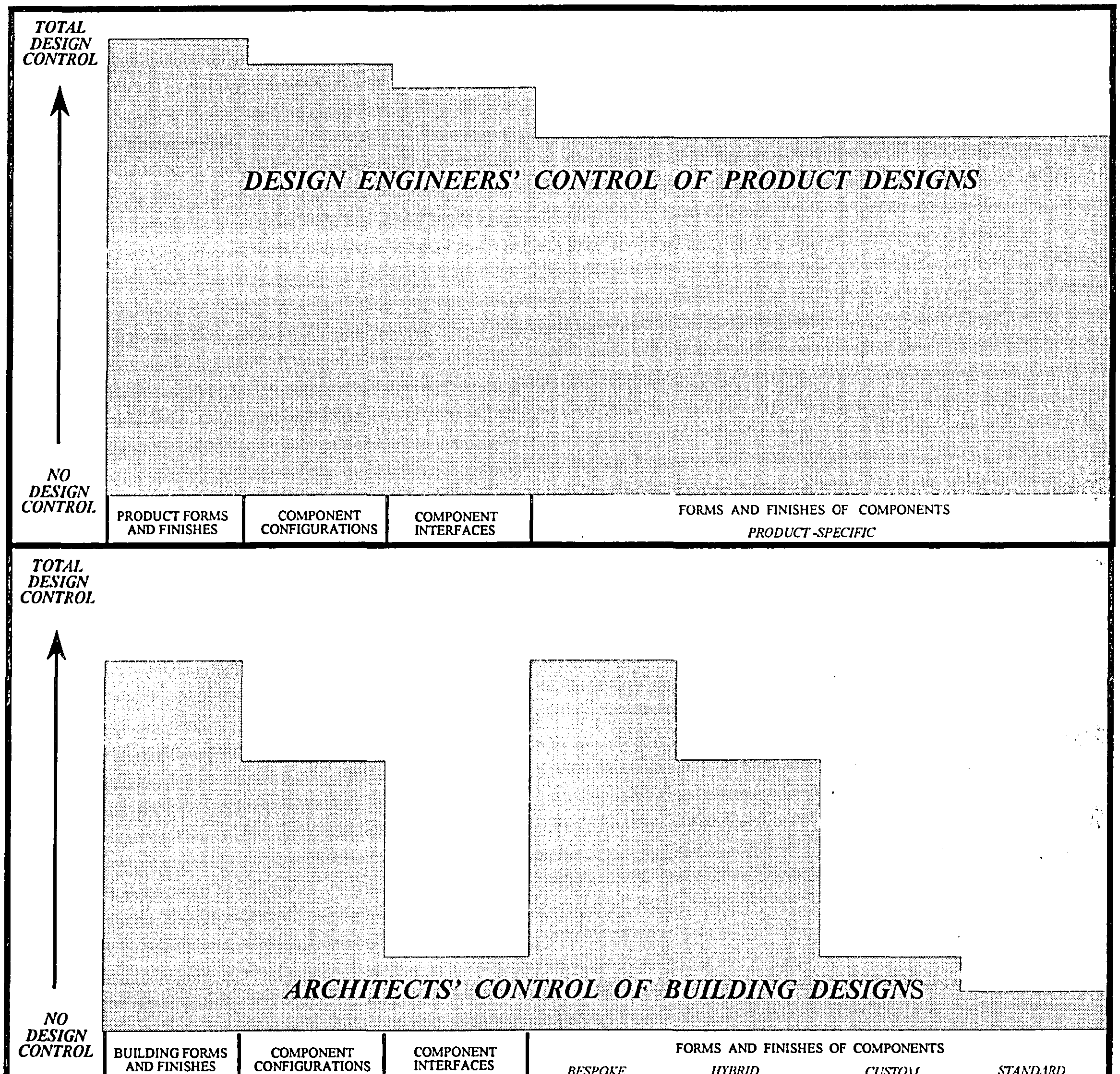


Figure 5.1: Control of the design process

very limited for Supplier-Y because the forms and finishes of the bespoke components which they manufacture change from one order to the next. It is seldom technically feasible to design moulds for manufacturing single piece assemblies because component forms and finishes cannot be determined before orders are received. Further, it is seldom economically viable to invest in moulds because there is little, or no, repetition of component forms and finishes. Even parts rationalisation is difficult because many parts which are visible are likely to be specified by the architect's design.

However, even if parts consolidation were to be possible for Supplier-Y, this could improve its manufacturing productivity and quality, but result in serious installation problems. This is because the components which Supplier-Y manufactures are generally installed towards the end of construction programmes. Consequently, they have to be carried up finished staircases and through doorways. If these components were dispatched as single pieces they could be very heavy and very difficult to handle. This could lead to damage to both the components and the building's finishes, as well as injury to operatives. This suggests that whilst having a smaller number of larger components to assemble into a product may radically improve productivity and quality in the manufacturing industry, it would not necessarily always have the same results in the construction industry.

The example of pre-fabricated building modules is now used to illustrate that the problems described above are not limited to Supplier-Y. Pre-fabricated modules are often used instead of constructing building areas, such as computer rooms and hotel bedrooms, at site (Barbour, 2000). If these modules are building-specific, they are not mass produced. The production quantity will be limited to the number required for the particular building. With the forms, finishes, configurations and interfaces of rooms changing from building to building, it is neither technically feasible nor economically viable to fully automate their manufacture.

These modules do not reduce the number of parts required to construct a building. However, they do allow building production to be carried out in factories, with each building module forming a completed assembly by the time it arrives at site. This can reduce the overall duration of a building's construction at site. Further, production productivity and quality can be easier to monitor and manage in a factory than on a building site. Nevertheless, the use of building modules does not necessarily improve the productivity and/or quality of building construction. One major problem is that modules are much larger than the loose materials which are traditionally used to construct rooms. If the building's structure has already been fully designed it may then not be possible to design modules so they can pass easily between the building's columns and beams into position. Further, even when the design of a building's structure and pre-fabricated modules are harmonised, there is still a risk of both the structure and the modules being damaged during installation. This is because of the problems of handling very large components at building sites. It is often necessary to use tower cranes, and control of these is far less precise than the control of robots in an automated factory, particularly in adverse weather conditions. However, consolidating parts for smaller building components, such as shower heater units, could improve the productivity and quality of both their manufacture and installation. Also, parts consolidation is more feasible and viable for standard building components because they can have a high repetition of pre-order design certainty. Further, DFM metrics are more applicable to discrete components such as shower heater units which are manufactured from engineered parts using batch and line production processes.

It is important to recognise, though, that even where DFM design rules and design metrics can be applied successfully to building components there may be some negative affects. For example, parts consolidation within building components could result in improved assembly quality and increased product reliability, but lead to component breakdowns being more serious. This is because if a sealed single piece assembly breaks down it can be complicated to repair and/or costly to replace. Parts consolidation can also result in product maintenance being more complex, requiring facilities and skills beyond those of the customer. In the construction industry, some of these problems associated with parts consolidation could apply to components such as electronic control systems for building ventilation.

It is not only DFM rules concerned with reducing part count that may be impractical in the construction industry, DFM rules concerned with automatic assembly may also be difficult to apply successfully. In the manufacturing industry, use of DFM has quite often led to the simultaneous design of components and product assembly tooling. However, as explained in Chapter 2, it is seldom possible for building component manufacturers to collaborate with architects in the development of building-specific assembly tooling. Despite considerable efforts to introduce automation into building construction over many years (Sangrey and Warszawski, 1985; Salagnac, 1990; Ibanez-Guzman, 1995; Howe; 2000), both construction plant (e.g. an excavator) and construction tooling (e.g. an excavator bucket) tend to be general purpose and manually operated (Syben, 1993). Moreover, it has been suggested that manufactured building components are made to fit into buildings designed and constructed using craft practices (Fisher, 1993). In this type of environment, common DFM strategies, such as designing components and assembly tooling at the same time, are neither technically feasible nor economically viable.

5.3.2 Manufacturing a design

Having identified that it may not be possible to apply some DFM rules and metrics to bespoke building components successfully, the practical problems caused by not using standard production design rules and standard production design metrics are now discussed. Examples of Supplier-Y's working practices are used to illustrate the issues considered.

Prior to the intervention, Supplier-Y continually reconfigured its general purpose production resources to manufacture each architectural drawing received. This approach of always manufacturing a design (MAD) is the opposite of design for manufacture, which seeks to match the design of a component to the capabilities of the processes that are used to deliver it. Prior to the intervention, some of the manufacturing productivity and quality problems associated with MAD were intuitively recognised. With regard to productivity, there was an awareness that both factory and site operatives spent some of their time trying to overcome production details which did not facilitate manufacture and/or installation. With regard to quality, it was perceived that there was a continual risk of non-conformances because drawings etc., were produced by different employees who gave their own individual interpretations to architects' information. Also, it was understood that where details were difficult to manufacture defects were more likely to arise.

Other productivity and quality problems associated with MAD were not recognised in the business. For example, without the aid of standard design procedures and rules to work to, employees tended to draw slightly different production details to each other. This results in potentially standard features, such as hinge positions, having a high level of unnecessary variation. As a consequence, opportunities to increase productivity by moving from job production to cellular and/or batch production are restricted. Also, without the aid of standard design metrics, estimating can also be erratic with some production times being high and some being low. This can result in operatives spending half their time having to rush their work unnecessarily: a situation which can often lead to quality problems.

Supplier-Y still has to prepare drawings from architects' concepts in the short time available between receipt of concept drawings and site installation (Lahdenpera and Tanhuanpaa, 2000). On many occasions, component designs are only completed after last minute modifications have been carried out at site, and "as built" drawings have to be issued. Also, even though the business frequently works with the same architects, component designs are seldom used on more than one building. This situation is recognised as being widespread in the construction industry (Tombesi, 2000). As explained in Chapter 2, this is because architects usually have to produce designs which satisfy the specific requirements of a particular customer at a single location, rather than the general requirements of a customer type in a global market. This means that there is less time to carry out DFM application, and fewer sales to spread the cost of application over, than in the design of components for manufactured goods.

Having illustrated the limitations of existing DFM rules and metrics, and the problems which arise from not having standard production design rules and evaluation metrics, the intervention is now described.

5.4 The Action Research Intervention

The action research intervention comprised four iterations of the cycle:

planning: analysing existing DFM methodologies, the business' outputs, and its operating environment;

acting: working within the business to guide the introduction of DFM principles;

observing: monitoring the adoption and impact of DFM principles within the business; and

reflecting: developing DFM principles to make them effective in the business' operating environment.

5.4.1 Cycle One

The first iteration introduced the concepts of standard production design rules and standard production design metrics into the business. These conceptswere initially seen as inappropriate for a bespoke manufacturing business. All examples of how DFM rules and metrics had been used successfully were dismissed, because they involved standard and custom goods where marketing / assembly companies dictate design to the customer. However, these concepts were eventually understood when business-specific examples were developed illustrating how they could be used to help the business improve productivity and quality by informing design decisions. For example, there was an awareness in the business that square cornered hinges take longer to fit than radiused hinges. This is because square corners cannot be formed with just a routing machine: a chisel has to be used as well. As shown in Stages 4 to 8 of Figure 4.2, these are the types of elementary motions that are defined and measured by DFM metrics. These metrics are not used to dictate design decisions: they are used to inform them. The form of one building may be enhanced by having hinges with radiused corners, whilst another may be enhanced by having hinges with square corners. In many cases it will not be a significant issue, and architects may specify hinges with square corners because they are not aware that hinges with radiused corners take less time to fit. With the aid of such examples, linking component features, like hinge geometry, to production times was eventually seen in the business as a way of guiding design decisions towards production best practice.

At the same time, it came to be recognised that much of craft practice could be standardised as design rules. For example, the position of a hinge from the bottom of a door was accepted as being 225 millimetres. However, some employees believed that this measurement was to the centre of the hinge, whilst others thought it was to the bottom of the hinge. It was recognised that this level of design decision was seldom of any significance to clients' or their architects, and that productivity and quality could be improved simply by setting hinge positions. This is because, if hinge positions for every order are predetermined, it becomes economically viable to fabricate a steel jig to guide cutting. This speeds up work and reduces the reliance on individual skill to achieve a good hinge fit. Further, the more dimensions that are pre-determined, the more quickly production information can be prepared, and the lower the risk of errors in doing so. This can cut administration costs and leave more time for production.

Achieving an acceptance that standard design rules and design metrics could be applied within the business was by far the most difficult part of the intervention. Subsequent iterations took less time and achieved more tangible benefits.

5.4.2 Cycle Two

Standard production design rules and standard production design metrics were formulated for the business during the second iteration. It was identified that this was necessary after analysis of existing DFM methodologies had made it clear that these were not suitable for a business manufacturing and installing bespoke building components. This was because their rules and metrics have been developed for standard and/or custom discrete engineered components, such as moulded parts, cast parts, sheet metal stampings and printed circuit boards. These types of components comprise different materials and parts, and require different types of production plant, to those manufactured by Supplier-Y. As a consequence, design rules were formulated by carrying out structured interviews of small groups of personnel. For example, site supervisors were asked how service furniture, such as reception counters, could be made simpler to install. There was common agreement that they should be manufactured for ease of disassembly. This was because operatives often wasted several hours at site trying to get large reception counters through building entrances, and usually ended up having to take them apart to do so. The same approach was used to identify which production operations were most common and should be developed into metrics first. The business' outputs were analysed to identify which rules and metrics could be applied to particular component types. This analysis revealed that some types of components had higher demand levels, less irregular geometry and more similar dimensions than others. For example, compound curved sash windows with unique geometry and dimensions were ordered for one-off renovation projects once every two or three years. At the other extreme, there was almost constant demand for doorsets, duct panels and cubicles with similar forms and finishes. This suggested that whilst it be technically feasible and economically viable to develop elementary motion level metrics for all outputs, it would only be possible to develop highly aggregated metrics for some outputs. As shown in Figure 5.2, the hierarchy of metrics can be defined as starting with elementary motions, such as "pick up chisel" and "pick up mallet". Even these rudimentary metrics can be linked to design features. For example, if a hinge has radiused corners there is no need to "pick up chisel" or "pick up mallet" to fit it to the edge of a door. These motion metrics can be aggregated up into activity metrics,

Figure 5.2: Examples of different levels of design metrics

Metric level	Example	Cost of formulating metric	Benefit of metric
Process	*Produce doorset*	*High*	*High*
Operation	*Produce door*		
Task	*Service door*	↕	↕
Activity	*Fit hinge*		
Motion	*Pick up chisel*	*Low*	*Low*

such as "fit hinge" and "fix hinge". Again these metrics can easily be linked to design features. For example, it takes considerably less time to fit a hinge with radiused corners than a hinge with square corners. However, it takes the same amount of time to fix both types of hinges. Activity metrics can be aggregated up into task metrics such as "service door for ironmongery". These task metrics can be further aggregated up into operation metrics, such as "produce door", and then brought together further as process metrics, such as "produce doorset". This level of aggregation was carried out within Supplier-Y for doorsets, duct panels, and toilet cubicles. The business does not produce above this level, however there are other companies which do. For example, a company providing pre-fabricated building modules produces at the building assembly level, and a business providing pre-fabricated buildings produces at the building product level.

Figure 5.3 below helps to illustrate how different levels of metrics can be used. A doorset is used as an example of a building component with a relatively low level

Figure 5.3: Example of how design metrics can be used

Lower variation building component e.g. doorset		Higher variation building component e.g. compound curved sash window	
Example	Level	Example	Level
Produce door frame	*Operation*	*Rip saw timber*	*Activity*
Produce door	*Operation*	*Dimension timber*	*Activity*
Produce glazed panel	*Task*	*Form curved sections*	*Activity*
Hang door in frame	*Activity*	*Joint window sashes*	*Activity*
Install door at site	*Activity*	*Glaze window sash*	*Activity*

of geometric and dimensional variation. Nearly every door manufactured by Supplier-Y was rectangular, with a high of 2040 millimetres, and widths of either

726 or 826 millimetres. The fact that these doors had a huge variety of finished colours does not affect metrics. What is important is the production time of applying the finish. For example, it takes longer to apply a paint finish than it does to press a plastic laminate onto a door. The colour of paint or plastic laminate does not matter unless it means that plant has to be cleaned before the next colour is applied. The business identified that there were twenty common types of door frames, thirty common types of doors and fifty common types of glazed panels which are cut into doors. The mathematical product of these common alternatives is thirty thousand design options. In contrast, the geometric, dimensional and demand uncertainty of components such as compound curved sash windows means that if operation level metrics are developed for them they may well never be used. The analysis also revealed that whilst detailed production drawings had to be prepared and approved for components such as compound curved sash windows, they were not a necessity for components with more regular geometry and common dimensions. This suggested that a procedure based on part lists, rather than on one based on drawings, could be introduced for applying rules and metrics to doorsets, duct panels and toilet cubicles during the preparation of production information.

5.4.3 Cycle Three

Standard production design rules and standard production design metrics were piloted in the business during the third iteration. By this stage of the intervention it was recognised that productivity and quality could be improved by applying DFM principles, but there was concern that application would be too time-consuming and costly. As a consequence, it was proposed that rules and metrics should be embedded into computer software which could automatically guide users through the business' standardised production design procedures. This led to an investigation of software options being carried out. Various solutions from turnkey installation of comprehensive proprietary business systems to writing individual programs internally using Visual Basic were considered.

Decision tree evaluation and multi-attribute utility analysis identified that a bespoke production resource planning package should be purchased and then configured within the business to suit its own requirements. This software was piloted with the preparation of production information for doorsets. Piloting began off-line with recently completed orders. Parallel on-line piloting was then carried out with current orders, using only employees who were already computer literate.

5.4.4 Cycle Four

Standard production design rules and standard production design metrics were fully integrated into the business' operating process during the final iteration. As a first step, the preparation of production information for all doorsets was carried out using the configurated proprietary software. This significantly reduced the time spent in pre-production and improved the visual quality of information. For the first time the majority opinion in the business moved from scepticism to enthusiasm. The approach was then extended to duct panels and toilet cubicles with similar results. The next step was to involve employees who were not computer literate. To facilitate this, the steps in the computerised design procedure were documented and used as the basis for one-to-one training. When the software is used, standard design rules are applied in the form of standard formulae which automatically calculate dimensions such as door widths. In this example, standard deductions are made from the structural opening size, which the user is prompted to enter by the software. These standard deductions are those agreed by experienced operatives as being most suitable for fixing door linings and hanging doors in linings. Standard production design rules are also applied in the form of attributes such as hinge positions. Standard production design metrics take the form of an electronic library of production times for alternative components sizes and alternative component features. For example, alternative widths of doors and alternative shapes of glazing apertures for doors. This library was structured and populated during the intervention, but nominated personnel in the business have controlled access to add new data and/or update data to accommodate changes in manufacturing process or materials etc. These standard production times are initially retrieved to prepare estimates. If the estimate is successful, the same production times are used in the preparation of factory schedules.

5.5 Intervention Results

5.5.1 Improved business processes

As a result of the intervention, Supplier-Y has a formal design method, which is used during the preparation of production information, for improving the productivity and quality of component manufacture and installation. The people in the business understand the purpose and use of the formal design method.

The introduction of the formal design method has contributed to a less turbulent working environment. For example, the working relationship between the estimating and production departments has improved, because production personnel now have far more confidence in the hours allowed for manufacturing and installation by estimators. This is due to the systematic flow of information which begins in the production department. Information is originated by applying standard rules to component production to improve production times, and metrics are then developed from actual times. The working relationship between office personnel and production operatives has also improved. This is because the preparation of production information relies far less on the availability of particular individuals with specific knowledge. Consequently, information bottlenecks have been reduced and there is a more balanced flow of information into the factories. This has reduced the amount of overtime which operatives have to work without prior notice.

5.5.2 Productivity and quality improvements

Figure 5.4 below shows the types of improvements which could, and could not, be achieved as a result of the intervention.

Figure 5.4: Improvements achieved, and not achieved, in Supplier-Y	
Development of production rules which make component manufacture easier	✔
Development of production rules which make component installation easier	✔
Establishment of production metrics which improve estimating and scheduling accuracy	✔
Computerisation of production rules which improve preparation of production information	✔
Computerisation of production metrics which improve estimating and scheduling	✔
Elimination of components which are not essential to building form and function	✘
Modification of component forms to simplify building construction	✘
Development of component-specific building construction tooling	✘
Consolidation of component parts to make component manufacture easier	✘
Development of component-specific manufacturing plant	✘

Computerisation of production design rules has resulted in faster preparation of more consistent production information. Further, because estimates are prepared using production metrics, it now takes less time to prepare accurate production information and factory schedules from them. Also, because manufacturing and installation issues are addressed during the preparation of production information, less time is spent having to supervise production and monitor quality. Overtime working due to late issue of production information and quality problems has also decreased.

Figure 5.4 also highlights that some the improvements often achieved as a result of applying DFM are not fully relevant to Supplier-Y. For example, building component manufacturers, such as Supplier-Y, are unlikely to volunteer to eliminate components which may not be essential to building form and function if doing so will result in reductions to their profitability and/or financial turnover. Further, although Supplier-Y may be able to modify the design of components so they are individually easier to manufacture and install, this will not necessarily make entire buildings simpler to construct. This is because individual building component manufacturers do not necessarily know how their components should be designed to make the construction of interfaces by other trades simpler.

Another example of an improvement which is not relevant to Supplier-Y is the consolidation of numerous parts into single piece assemblies. As described in Chapter 4, this can lead to large assembly time reductions for standard and custom goods such as printers. However, as discussed in section 5.3, because of design uncertainty, it is neither feasible nor viable for bespoke building component manufacturers to invest in parts consolidation.

Nevertheless, applying the fundamental principles of DFM, standard production design rules and standard production design metrics, can have a significant impact on business performance. For example, as a result of this intervention,

Supplier-Y's non-productive costs have fallen by forty-seven percent whilst its financial turnover has increased by twenty percent.

As described in section 5.3, Supplier-Y measures non-productive costs as a proportion of annual financial turnover. Supplier-Y does not measure output per production operative because of the difficulties of applying an objective measurement. For example, sprayers apply lacquers to a large total area of component surfaces each week, but it is the small area of finishing touches which are applied by the French Polisher that ensure client satisfaction. Also, the most highly skilled operatives tend to assemble the most complicated components. These components are often "loss leaders" which offer little or no profit.

Instead of measuring output per operative, Supplier-Y measures the total cost of employing production operatives as a proportion of annual financial turnover. This cost did not change significantly because, after several years of wage stagnation, there were substantial wage increases during the period of the intervention. This was because of higher general demand for production operatives in the surrounding area, and increased construction industry demand for production operatives throughout England (Ball *et al*, 2000).

Also, the introduction of DFM principles did not have a significant impact on material costs. Some common material and part types were rationalised as a result of introducing standard production design rules, but component design uncertainty prevents reduction of unit costs through bulk buying. Further, there was no reduction in material inventories. This is because in bespoke building component production materials are bought-in for each individual order: a practice which prevents the accumulation of inventories. In contrast, the reduction of inventories has been a major benefit of parts consolidation resulting from DFM applications in the manufacturing industry (Harding, 1999). This illustrates again that even if it were possible to apply existing DFM methodologies to bespoke building components, this would not necessarily result in reductions to production costs.

Nevertheless, the benefits of the intervention have been far reaching. In particular, it has made it possible for Supplier-Y to increase its financial turnover whilst remaining at its existing location. This is because the utilisation of people and plant has been improved by the introduction of standard production design rules and metrics. Prior to the intervention, increases in orders had always resulted in the need for additional personnel to prepare production information. This, in turn, had resulted in the need for more office space. Supplier-Y has no more space available for development at its current location. Now, however, the business is able to increase the number of orders which it processes without having to relocate to accommodate additional personnel. More increases in financial turnover are feasible because the analysis of historical manufacturing information for process improvement and future optimisation of resources has been made much easier by having a standard framework for production information.

5.5.3 Costs of the intervention

The direct financial costs of the intervention were incurred by employing a graduate manufacturing systems engineer for two years, purchasing three new workstations of computer hardware and additional computer software. There was also the opportunity cost of the time spent by salaried employees working on the intervention when they would otherwise have been working on something else. This did not exceed one man year in total. Some of these costs were recovered by cost savings achieved in the second year of the intervention, and it is forecast by the business that its remaining costs will be fully paid back early in the first year following the intervention.

5.5.4 Validity of the results

In this type of research scenario, it is very difficult to isolate the affects of an intervention. However, there are several factors which suggest a valid cause and effect relationship between this intervention and the forty-seven percent reduction in non-productive costs. For example, during the intervention, the business served the same markets with the same types of components as it had done before the intervention. Further, before the intervention, the business had invested heavily in new premises, up-to-date plant and employee training. Improvements in productivity and quality had arisen from these investments but these had plateaued. Also, during the intervention, no other improvement initiatives were attempted.

5.6 Designing Building Components to Improve Building Construction

This research has demonstrated that DFM principles can be applied to bespoke building component designs, and that their application can improve the productivity and quality of component production. As existing DFM methodologies have already been applied to standard building components with similar results (Cox *et al*, 1999), there is now evidence to suggest that DFM can improve the production productivity and quality of all building components.

However, designing components so they are individually easier to manufacture and install will not necessarily make buildings simpler to construct. As described above, existing DFM methodologies, in the manufacturing industry, focus on making components simple to assemble into whole products first, before making those components as easy as possible to manufacture. The application of these methodologies is directed by marketing / assembly companies which dictate product designs to their customers through a range of standard component options. In contrast, Supplier-Y receives no such direction from first level suppliers (i.e. principal contractors), clients (e.g. property developers), or end-users (e.g. building tenants). It is significant that Supplier-Y manufactures and installs components for some clients who repeatedly develop similar buildings, and for some principal contractors which repeatedly manage the construction of similar buildings. The business has no experience of any of these clients and contractors providing them with direction, or even advice, on how to design components for ease of construction. The business does have an understanding of how interfacing components and various construction processes can damage their own components. However, this is not sufficient for it to develop standard design rules which focus on improving the ease of overall building construction.

It could be suggested that architects should provide bespoke building component businesses with designs that ensure ease of construction. However, in the manufacturing industry it is not considered likely that design engineers, building designers' counterparts, will always design components that will ensure ease of product assembly. Accordingly, design engineers working in marketing / assembly companies have been provided with DFM methodologies. They have been provided with these methodologies, because in the manufacturing industry it is recognised that the productivity and quality assembly will not be consistently improved if doing so relies upon the varying experience and knowledge of individual designers.

5.7 Chapter Conclusion

This chapter has described an action research intervention designed to determine whether DFM principles can be successfully applied to building components. An overview of the research setting and the research method which was used has been provided. Component design in the construction industry has been compared with how DFM is used during component design to improve productivity and quality in the manufacturing industry. Each stage of the intervention has been described in detail and the results of the intervention have been reported. Issues affecting the use of component design to improve building construction have been discussed. The principle findings of this part of the research are stated below.

During the intervention, it was identified that existing DFM rules and metrics are not alway applicable to bespoke building components. This is because many DFM rules and metrics have been developed for materials, parts, plant and processes which are not always used in the manufacture of building components. It was also identified that some of the improvements associated with the application of existing DFM methodologies to standard and custom goods are not relevant to bespoke building components. These include development of component-specific manufacturing plant and component-specific construction tooling.

Most significantly, the intervention demonstrated that the application of DFM principles can be successful in improving the productivity and quality of building component production. Further, it has been demonstrated that application of DFM principles is both technically feasible and economically viable for the many small-, and medium-sized businesses which manufacture building components. Furthermore, the intervention demonstrated that application of DFM principles to building components can lead to significant organisational and financial business benefits. In this case, the main organisational benefits are better working relationships between the estimating and production departments in particular, and between office personnel and production operatives in general. The main financial benefits are:

Supplier-Y's non-productive costs have fallen by forty-seven percent, whilst its financial turnover has increased by twenty percent.

6.0 Study II: Applying DFM Principles to Buildings

6.1 Introduction

This chapter describes the case study designed to determine whether DFM principles can be successfully applied to whole buildings.

As described in Chapter 4, existing DFM methodologies help product designers take the lead in the development of components which are simple to assemble into whole products. However, this approach is seldom possible in the construction industry because architects and consultant engineers have limited authority over the designs of standard building components. Indeed, the research has determined no evidence of building designers or building contractors providing component producers with direction on how to design components for ease of construction. Further, as discussed in Chapter 5, producers of both standard and bespoke components are not necessarily able to design components which make buildings easier to construct because they often lack the comprehensive knowledge required to do so.

The objectives of this case study were to determine how DFM principles could be applied where building designers have limited influence over component design; and whether DFM principles would be successful in improving construction productivity and quality where common DFM strategies, such as parts consolidation, can seldom be implemented.

6.2 Case Study Overview

6.2.1 The case study setting

The central research activity of the case study was a trial application of DFM principles during the construction of a healthcare facility by Contractor-X. Construction was carried out from 1997 to 2000 and cost over £75 million. Healthcare facilities are widely recognised as being particularly difficult to construct because of their complexity (Chan, 2000).

DFM principles, which are described later in this chapter, were applied to the design of assisted bathrooms contained within the healthcare facility bedrooms. These are an essential requirement for patients who cannot bathe without the help of nursing personnel. The assisted bathroom drawings had already been fully developed for construction, however, Contractor-X sought additional development of the assisted bathroom design because of exacting construction and usage requirements.

During construction, the floors of assisted bathrooms have to be laid to complex patterns of shallow falls in a very restricted area, robust joints have to be formed between floor and wall coverings, and items of equipment, such as seats, have to be securely fixed. Further, the specialist components and processes which can achieve the required functionality are far less versatile than traditional building materials and craft practices. For example, the walls of assisted bathrooms have traditionally been covered with ceramic tiles. Now, high performance vinyl sheets are used instead, but the fixing and jointing of these sheets requires specific tools and techniques. In contrast, ceramic tiles were fixed in assisted bathrooms using the general tools and techniques that any DIY enthusiast might use to tile a bathroom at home. During use, the durability of assisted bathroom construction is critical, as any lifting of floor coverings etc., could result in injury to patients and/or nursing personnel. Also, if assisted bathrooms cannot be used after completion of the healthcare facility, because of poor construction, a non-availability penalty will be charged to the contractor by the client.

As a result of these exacting construction and usage requirements, assisted bathroom designs have to define precisely how materials must be placed, how components must be installed, and how their interfaces must be constructed: details cannot be "made to work" by operatives during construction. It is very important for construction to be right first time because programmes and working space are tight, with extreme demands being placed on everyone involved. Photographs of an assisted bathroom are included in section 4 and section 5 of this chapter.

The building, and its assisted bathrooms, were bespoke. The case study focused on the application of DFM principles to a bespoke design because, as explained in Chapter 4, that is the most challenging application for an approach most successfully applied to the design of standard goods.

6.2.2 The case study research

The case study began in January 1999 and was completed in May 2000. The research was carried out with Contractor-X in the four stages listed below.

- Stage 1: Obtaining approval for trial application of DFM principles.
- Stage 2: Preparing for trial application of DFM principles.
- Stage 3: Carrying out trial application of DFM principles.
- Stage 4: Measuring results of trial application of DFM principles.

During Stage 1, approval for the trial application of DFM principles was obtained from Contractor-X's Head Office. There was initially some uncertainty as to whether the trial would be worthwhile. Approval was obtained after responses to attitude statements contained in a postal questionnaire demonstrated support for the application of DFM principles. This stage of the case study is described in section 6.3. It started in January 1999 and took four months to complete.

During Stage 2, support for the trail application of DFM principles was obtained from personnel based at the healthcare facility construction site. Support was obtained after responses to structured interviews carried out by the author revealed serious concerns about assisted bathrooms details. The interviewees were personnel who had been involved in their design and the personnel who would be involved in their construction. This second stage started in May 1999 and took four months to complete. It is described in section 6.4.

During Stage 3, the trial application of DFM principles was carried out. It took place during a design co-ordination meeting dealing with the assisted bathrooms. The meeting took place in September 1999 and was held at Contractor-X's site offices. It was attended by a total of ten representatives from the architect, Contractor-X and sub-contractors. During the meeting, attendees carried out design evaluations and design improvements using DFM principles. This third stage of the case study is reported in section 6.5.

During Stage 4, the results of the trial application of DFM principles were measured. This final Stage started immediately after the field trial and continued until May 2000. Productivity and quality improvements were measured at site. Further, anonymous questionnaires were used to measure attitudes towards the application of DFM principles. Finally, after results had been gathered, a meeting was held at Contractor-X's Head Office to discuss whether further applications of DFM principles would be beneficial. This final stage of the research is described in section 6.6.

6.3 Case Study Stage 1: Obtaining Approval for the DFM Field Trial

6.3.1 Framework for DFM principles

Initially, Contractor-X's personnel regarded standard production design improvement rules and standard production design evaluation metrics as being inappropriate for bespoke buildings. Examples of how DFM rules and metrics had been used successfully were dismissed as irrelevant, because these examples involved standard and custom manufactured goods where marketing / assembly companies dictate design to customer types. In order to obtain approval for the DFM field trial, a description of a Framework for DFM principles which could be applied during the design and construction of bespoke buildings was developed.

This description, which is shown below, was refined during the course of eight piloting iterations with an architect, a construction manager, a commercial manager, and managers from a supplier and a sub-contractor. These industry practitioners were either employed by, or worked with, Contractor-X.

Framework for DFM Principles

Suppliers and subcontractors meet with consultants, using standard Workshop guidelines to optimise the cost and performance of individual materials, parts and services. These are then integrated for the maximum benefit of clients[1]*. The design information generated during these Workshops is converted into standard data*[2] *that communicates those material, part and service features which affect costs and benefits and how they do so. These data enable project participants to understand each other's operational requirements. On subsequent projects these data are the base from which participants work together.*

[1] The term, "Workshop guidelines" was used instead of standard production design improvement rules. This is because, interview findings and piloting responses suggested that, whilst attending meetings to "sort out" designs is commonplace, the concept of standard production design improvement rules is not recognised.

[2] The term, "Standard data" was used instead of standard production design evaluation metrics. This is because, interview findings and piloting responses suggest that, whilst referring to data sheets is commonplace, the concept of standard production design evaluation metrics is not recognised.

The Framework does not distinguish between different types of buildings, building clients or modes of building procurement. This is because standard production design rules and metrics have to transcend these issues in construction, just as they have done so successfully in manufacturing. Consider the example of one DFM design rule associated with assembly practice, "ensure adequate access and unrestricted vision". This rule could be applied to manual production operations, whether in an assembly factory or on a construction site. Design metrics can also be transferrable. Consider the example of metrics for door production provided in Chapter 5. One time metric might indicate that it takes longer to fit a door hinge with square corners than a door hinge with radiused corners.

These kind of elementary motion metrics can inform architects' decisions when any building is being designed, irrespective of the type of client and/or mode of procurement. There is already an example of a standard combined rule and metric being applied in all the procurement and production arrangements which can be found in the construction industry. This is the ergonomics rule "twice the rise plus the going must equal between 550 and 700 millimetres" (Mitchell, 1982). This ergonomic rule ensures that staircases are designed so that every able bodied person is able to climb them comfortably. The distance of 550 millimetres to 700 millimetres covers the span of average strides. The term "going" describes the tread depth. The term "rise" is used to describe the tread height. The rule stipulates, "twice the rise" because twice as much effort is required to lift one's foot up "the rise" than is required to pass one's foot across "the going". There are a huge diversity of staircases manufactured and installed in the UK, but all of them conform to this one standard combined rule and metric.

6.3.2 Demonstrating support for DFM principles

The Framework for DFM principles was regarded as being practical by key personnel at Contractor-X's Head Office. However, they considered that the opinions of consultants, building component manufacturers and building component assemblers should also be gathered, as their participation would be required in the trial application.

To address this requirement, three sets of attitude statements relating to the Framework were developed. In the final section of the postal questionnaire referred to in Chapter 4, consultants, manufacturers and assemblers who worked with Contractor-X were asked to indicate the extent to which they agreed or disagreed with the three sets of attitude statements. An ordinal scale was used, with 5 representing strong agreement and 1 representing strong disagreement.

Using the Statistical Package for Social Sciences (SPSS), responses were analysed according to the Kruskal-Wallis 1-Way test in order to obtain a preliminary mean ranking scale of importance. Responses were then rank scored to provide an indication of significant differences by applying the Mann-Whitney U-Wilcoxon Rank Sum W test. Further, actual responses were related to the median response by carrying out the Wilcoxon Matched-Pairs Signed-Ranks test. Full details of the attitude statements, and their analyses carried out are contained in Appendix F.

Table 6.1 indicates the agreement shared by all types of respondent that introduction would improve equally the following aspects of the construction process: communicating project information, specifying components, programming construction, and selecting suppliers and contractors.

Table 6.1: Overall sample ranking of potential construction process benefits	
Rank	Potential benefit
= 1	Improve the flow of project information between participants
= 1	Reduce the number of changes to specifications
= 1	Set more realistic programmes
= 1	Avoid inappropriate supplier / contractor selection criteria

The statements concerning potential time and cost benefits for individual organisations, which are shown in Table 6.2, all received either agreement or strong agreement. However, the grouping of results suggests respondents believed that the time reductions would be more significant than cost reductions.

Table 6.2: Overall sample ranking of organisations' potential time and cost benefits	
Rank	Potential benefit
= 1	Reduced minimum lead times
= 1	Reduced minimum time to fulfil an order
3	Reduced fixed cost in relation to financial turnover

Table 6.3 shows the broad agreement amongst all types of respondent that introduction would provide equal opportunities to reduce the costs of constructing five building elements. These elements were: mechanical and electrical services; envelope; finishes; superstructure; and roof. When analysed as an overall sample, results indicated that respondents were only undecided about reductions to the costs of constructing substructures.

Table 6.3: Overall sample ranking of construction cost reduction opportunities

Rank	Building element
= 1	Mechanical and electrical services
= 1	Building envelope
= 1	Finishes
= 1	Superstructure
= 1	Roof
6	Substructure

Responses to these three sets of attitude statements indicated to senior staff at Contractor-X that there is an awareness of the limitations of existing design methods in the construction industry, and that the introduction of the proposed Framework for DFM principles could receive support from a range of construction organisations. As a consequence, approval was given for a trial application of DFM principles to be carried out.

As well as leading to approval for a trial application of DFM, the analysis of attitude statements also resulted in the significant research finding described below. Separate analyses of the three types of respondents to attitude statements about potential cost reductions, revealed that over half of manufacturers and assemblers were undecided about whichever five building elements they did not have direct involvement with. For example, more than fifty percent of respondents involved in Mechanical and Electrical services were undecided about potential cost reductions with regard to building envelope, finishes, superstructure, roof and substructure. In contrast, only one consultant was undecided about five building elements. These results suggest that manufacturers' and assemblers' understanding of construction costs is often limited to their own component type. This finding suggests that manufacturers and assemblers do not have the comprehensive knowledge required to design components which improve the ease of overall building construction.

6.4 Case Study Stage 2: Preparing for the DFM field trial.

6.4.1 Obtaining support for the field trial

A challenging application for DFM principles was sought. This led to the identification of a large, complex, bespoke healthcare facility building which was being constructed under the management of Contractor-X. An initial meeting at site was arranged by Contractor-X's Head Office. During this meeting, it became apparent that Site Office personnel were unsure as to whether the application of DFM principles would be worthwhile. However, they saw it as being in their own interest to try any means open to them to develop further the designs of assisted bathrooms. This was because the Site Office personnel had managed the construction of similar assisted bathroom designs and were aware that problems had subsequently arisen during their use. They did not want this to happen again, particularly as a penalty would be charged to Contractor-X if assisted bathrooms were not available for use after completion of the healthcare facility.

As a result, a further visit to Contractor-X's Site Office was arranged. During this second visit, ten semi-structured interviews were carried out to gather opinions about the designs of the assisted bathrooms. The interviews were carried out by the author and lasted approximately thirty minutes each. All of the interviewees had been involved in the design of the assisted bathrooms or were going to be involved in their construction. Their responses revealed serious concerns about assisted bathrooms details. Full details of the interviews, including a sample interview schedule, are provided in Appendix G.

An assisted bathroom is formed by partitioning an area 3 metres by 2 metres within a healthcare facility bedroom. The partition is constructed from standard proprietary metal framework sections and standard sheets of plasterboard. The partition includes a full height door.

Figure 6.1 shows the full height door. In this photograph, the door is opened outwards, and the WC within the assisted bathroom is visible. As well as a WC, a hand basin and shower complete with half height folding screen and seat are contained within each assisted bathroom.

Figure 6.1: Open door into assisted bathroom

Although there is a shower in each assisted bathroom, there is no shower tray. Instead the floor is constructed from sand and cement screed laid in a complex patterns of shallow falls into a drainage point in the centre of the shower area. The screed is covered with non-slip vinyl which is dressed into a stainless steel grill at the drainage point. The walls are covered with smooth vinyl. Shower pipes pass through the vinyl and the partitioning. Shower screen brackets and shower seat brackets are fixed through the vinyl onto the partitioning.

Figure 6.2: Closed door into assisted bathroom

Figure 6.2 shows the full height door into the assisted bathroom in its closed position. The door with the side panel in the background of the photograph is the door into the bedroom.

The interviewees shared a common agreement that the design would be difficult to construct. Access during construction was a common concern. This is because assisted bathrooms are small in area, which leaves little room available for construction tasks such as rolling out vinyl sheets to facilitate accurate cutting. Also, space to carry out small movements, such as connecting pipes behind WC access panels, was limited. Vision during construction was also regarded as being a problem. This is because the assisted bathroom have no windows and temporary lighting at site is often difficult to retain and hard to position, particularly in the limited area of an assisted bathroom. Further, interviewees were all concerned that, even if access and vision were good, it would be very easy for the design to be constructed incorrectly because of its complexity.

When the general concern about the assisted bathroom design had emerged as a result of the interviews, Contractor-X's site office personnel agreed that a trial application of DFM principles should take place.

6.4.2 Selection of DFM principles

Consideration of interviewees' responses resulted in the two existing DFM design improvement rules stated below being selected for application.

- "Ensure adequate access and unrestricted vision".
- "Design parts that cannot be installed incorrectly".

In contrast, no existing DFM metrics were found to be available for the assisted bathroom designs. However, in order to trial DFM principles, equivalent metrics needed to be developed. Accordingly, an ordinal rating system was devised. This system was applied during the trial and resulted in the generation of metrics which could be used on subsequent occasions for design evaluation.

Evaluations of alternative designs was based on an ordinal rating scale of 0.1 to 1.0, where 0.1 = the designed detail would be constructed right first time, within the agreed time and for the agreed costs, in 10% of attempts, 1.0 = the detail would constructed right first time, within the agreed time and for the agreed costs, every time.

The metrics defined during the case study are consistent with those found in existing DFM methodologies in two key respects. Firstly, the evaluation data now found in DFM methodologies has been developed and refined over many years: they were not immediately available in their current sophisticated form (Boothroyd and Radovanovic, 1989; Knight 1991). Secondly, DFM evaluation data provide only rough estimates: they are effective because they communicate the likely production differences between alternative designs (Dewhurst, 1988). Similarly, as shown in the next section, the standardised rating system used in the case study communicates the likely construction differences between alternative designs, and thereby reveals the best available design.

6.5 Case Study Stage 3: Carrying out the DFM Field trial.

6.5.1 Trial application procedure

DFM principles were applied during a design co-ordination meeting which was facilitated by the author. The four step procedure stated below was used.

1. Evaluate existing assisted bathroom design;
2. follow design rules to improve existing design;
3. evaluate and compare alternative designs; and
4. agree implementation actions.

Figure 6.3 below, shows the form which was used by the ten industry practitioners who attended the meeting to record their design evaluations, design improvements, and levels of participation. This form, in A3 paper size, was issued to all attendees at the beginning of the meeting. Attendees were guided in its use by the author. In addition, structured observation schedules were used by independent non-participants to record the pattern of attendees' involvement.

All of the ten attendees had been involved with the design of the assisted bathrooms and/or would be involved in their construction. Contractor-X's project manager attended, as did the senior project architect. The remaining eight attendees were representatives from the companies which were responsible for the following activities: screeding floors, laying vinyl floor coverings, erecting partitions, placing vinyl wall coverings, fixing suspended ceilings, installing electrical equipment, plumbing in shower etc., and installing ventilation equipment.

Figure 6.3: Form used by meeting attendees to record their design evaluations, design improvements and their own levels of participation

NB	*When using this form, please write (in block capitals) relevant details in the spaces provided, where number scales are provided please circle only one choice per row.*											
1. MEETING DETAILS	MEETING DATE			MEETING PERIOD NUMBER		MEETING LOCATION						
	YOUR NAME				YOUR ORGANISATION				YOUR WORK			
2. DETAILS OF EXISTING DESIGN	BRIEF DESCRIPTION OF DESIGN											
	YOUR EVALUATION RATING		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	CONSTRUCTION PROBLEMS											
	AVERAGE EVALUATION RATING		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
3. DESIGN RULE												
4. DETAILS OF ALTERNATIVE DESIGN	BRIEF DESCRIPTION OF DESIGN											
	DESIGN IMPROVEMENTS											
	YOUR EVALUATION RATING		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	CONSTRUCTION PROBLEMS											
	YOUR ORGANISATION'S **ACTIONS**	ADDED										
		OMITTED										
	YOUR ORGANISATION'S **RESOURCES**	ADDED										
		OMITTED										
	AVERAGE EVALUATION RATING		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
5. PARTICIPATION	PLEASE RECORD THE PERCENTAGE OF YOUR TIME SPENT FOCUSING ON THE CONSTRUCTION DETAIL, i.e. analysing, clarifying, developing, evaluating, explaining, listening, refining, selecting?											
EVALUATION SCALE	*0.1 = the detail would be constructed right first time, within the agreed time and for the agreed cost, in 10% of attempts, 1.0 = the detail would constructed right first time, within the agreed time and for the agree cost, every time.*											

6.5.2 Evaluation of existing design

At the start of the design co-ordination meeting, information about the assisted bathroom design was discussed with the aid of relevant detail drawings. Evaluation of the existing design was carried out by asking attendees on what percentage of occasions they believed that the existing details could be constructed right first time. The mean response for the existing detail was 50% which, using the ordinal scale, gave an evaluation rating of 0.5. Attendees were immediately informed of the mean response and asked whether they would like to revise their evaluations. None wished to do so. The fact that those collectively responsible for a building detail believed that it would only be constructed right first time on fifty percent of occasions suggested that there was considerable scope for improvement.

6.5.3 Improving existing design

Users of existing DFM methodologies integrate production best practice into their designs by following DFM procedures which guide them in the use of universal design rules. In this case study, two rules were applied.

Rule 1: "ensure adequate access and unrestricted vision".

Rule 2: "design sub-assemblies that cannot be constructed incorrectly".

The wording of Rule 1 was not adapted from that of the original DFM rule. The wording of Rule 2 was adapted from the original DFM rule, "design parts that cannot be installed incorrectly". The original DFM rule refers only to parts installation because the manufactured goods to which existing DFM methodologies are applied tend to comprise discrete parts. In contrast, bespoke buildings consist of bespoke sub-assemblies comprising: formless materials, such as screed; formed materials, such as vinyl flooring; and discrete parts, such as waste outlets.

As described below, application of these two rules resulted in the design improvements shown in Figure 6.4.

Figure 6.4: Design improvements

DFM design rule applied	Detail	Design improvement
Rule 1 *Ensure adequate access and unrestricted vision*	WC panels	Framing section reduced
	Wall vinyl	Weld moved from corner
Rule 2 *Design sub-assemblies that cannot be constructed incorrectly*	Floor screed	Specific batch recipe defined
	Wall penetrations	Use of neoprene gaskets

Discussion amongst attendees focused on Rule 1 resulted in two design improvements. Prior to the application of DFM principles, the space behind WC access panels did not provide adequate access for plumbers to carry out pipe connections. However, reducing the size of framing sections rectified this problem.

Figure 6.5 shows the WC access panel. This is the white horizontal panel with the hardwood edging.

Figure 6.5: WC access panel

Also, wall vinyl had previously been welded in the corner, a position which did not provide adequate vision for the welder. Moving the weld round from the corner made it much simpler to construct the watertight weld which is critical to the durability of the assisted bathroom.

Figure 6.6 shows the corner of the shower area. This photograph also shows the shower head and shower control dial.

Figure 6.6: Corner of shower area.

Typically, the use of DFM methodologies results in the redesign of processes as well as products. Similarly, in this case, defining the optimum recipe for the floor screed, and ensuring that it was adhered to, was a process modification.

Figure 6.7 shows the floor screed in the shower area. The modification to the screed emerged when the discussion focused on Rule 2 revealed that the detail could easily be constructed incorrectly.

Figure 6.7: Floor screed to shower area

Also, the use of sealant around exposed pipework passing through wall vinyl was seen as a detail which could easily be constructed incorrectly. To rectify this problem, neoprene gaskets were suggested in order to provide a foolproof watertight seal. The shower head fixings shown in Figure 6.6 above are example of the pipework to which neoprene gaskets were added.

6.5.4 Evaluation and comparison of alternative designs

The assisted bathroom design was then evaluated incorporating the improvements described above. As before, the attendees were asked to indicate on what percentage of occasions they believed that the existing details could be constructed right first time. The revised design received a mean rating of 0.59: an eighteen percent improvement on the rating of 0.50 for the existing design.

Two further design alternatives were then considered for evaluation. These were: the existing detail but with a prefabricated shower unit (instead of shower unit constructed from loose materials and parts), and a completely prefabricated assisted bathroom module. A thorough explanation of these two alternatives was provided during the meeting by their manufacturers. Their explanations included presenting samples, discussing written material, and answering questions.

As shown in Table 6.4 below, both of these two alternative options received higher ratings than the existing design and the modified design. However, they could not be considered for use in the construction of the target healthcare facility because it was already too late in the procurement process.

Table 6.4: Evaluation of alternative designs by Meeting attendees

Design option	Mean ratings	Consensus amongst attendees
Shower cubicle	0.81	90% (ranked 2nd by one attendee)
Bathroom pod	0.79	90% (ranked 1st by one attendee)
Modified existing	0.59	100% (ranked 3rd by all attendees)
Existing design	0.50	100% (ranked 4th by all attendees)

6.5.5 Agreement of implementation actions

As it was too late in the procurement process to adopt either the shower cubicle or bathroom pod alternative, agreement of implementation actions dealt with the modified version of the existing design.

The quality of vinyl welding emerged as an area of particular concern. It was agreed that the number of welds carried out by one operative in one session should be restricted. It was also agreed that only nominated, highly skilled, operatives would carry out the work. This would involve no extra cost, only more appropriate allocation of existing labour resources.

This need to re-engineer processes as a result of DFM application is consistent with the results of DFM application in the manufacturing industry. For example, to achieve the cut in printer assembly time from 30 minutes to 3 minutes previously stated in Chapter 1, major changes to job specifications, plant investments, facility layouts were inevitably required. Further, the need to design processes to suit particular levels of skills is vital to achieving high levels of productivity (McKinsey, 1998). Similarly, the laying of floor screeds was regarded as being a process which should be improved. As a result, it was agreed that experimental floor areas should be laid with recorded mixes until an optimum recipe was identified. Then, the same optimum mix would be used for every assisted bathroom in the healthcare facility. This initial effort was seen as insignificant compared to the abortive mixing and material wastage which it would prevent during construction.

6.6 Case Study Stage 4: Measuring results of the DFM field trial

6.6.1 Construction productivity and quality benefits

In the months following the meeting, the productivity and quality results of applying DFM principles were monitored by Contractor-X. The results of their observations are shown in Table 6.5 and described below.

Table 6.5: Construction productivity and quality benefits

Design rule applied	Detail	Benefit
Ensure adequate access and unrestricted vision	WC access panels	Reduced production time and cost
	Wall vinyl	Reduced rework cost
Design parts that cannot be installed incorrectly	Floor screed	Reduced production time and cost
	Wall penetrations	Reduced rework cost

Construction productivity benefit is defined for the purpose of this case study as, "reduced construction time and cost". Contractor-X confirmed that modification of WC access panels led to a saving of just over one man week of work for the plumbing contractor. Similar improvements were achieved by use of the optimum floor screed recipe during construction. There is no one single definition of construction quality (Knutt, 2000). For the purpose of this case study, construction quality benefit is defined as, "reduced rework cost without increased prevention costs during the construction and defects liability period". This definition is a rule of thumb measure, which does not take into account other potential savings, such as reduced material waste and other avoidable process losses (Love *et al*, 1998). The relevant specialists attending the meeting forecast that the rework costs to wall vinyl welds and wall penetrations would be reduced by at least eighteen percent.

The foregoing description of construction benefits has dealt with productivity and quality separately. However, although the correlation between improved construction quality and improved construction productivity is seldom clear and cannot be easily measured (Langford et al, 2000), they can often be linked. For example, where quality is improved construction productivity may rise because there will be fewer disruptions to operatives' programmed work as a result of them having to carry out rework (Thomas and Napolitan, 1995). In this case, the overall productivity of operatives laying vinyl may have been improved slightly because of less rework being required in assisted bathrooms.

Overall, the results show that construction productivity and quality benefits could be achieved from application of DFM principles.

6.6.2 Organisational benefits

At the end of the meeting, attendees completed an anonymous questionnaire. They were asked to indicate the extent to which they agreed or disagreed with attitude statements concerning the application of DFM principles. An ordinal scale was used (5 = strongly agree, 1 = strongly disagree), and responses to each statement were added together then divided by the number of responses to give the mean. This simple analysis was considered appropriate as only ten respondents were available.

As shown in Table 6.6 below, there was common agreement amongst meeting attendees that significant organisational benefits had resulted from applying DFM principles. In particular, attendees believed that they had developed a better understanding of other organisations' cost drivers. A sample questionnaire is contained in Appendix H.

Table 6.6: Perceived benefits of applying DFM principles

Perceived benefit	Mean of responses
Improved understanding of cost drivers	4.09
Improved understanding of operational problems	4.00
Improved working relationships	4.00

6.6.3 Costs of applying DFM principles

The results of the case study suggest that construction cost savings arising from the application of DFM principles would exceed the costs of their application. In this case study, the construction cost savings were at least two man weeks for skilled operatives.

If DFM principles were applied during the meetings which, as reported in Chapter 4, are routinely held to "sort out" designs, the costs of their application would be negligible. Moreover, the duration of such meetings could be reduced if attendees become more conversant with standard production design improvement rules. Also, the frequency of such meetings could be reduced if standard production design metrics evaluation metrics are developed to inform designers' decision making.

6.7 The Transferability of Case Study DFM Principles

6.7.1 The transferability of production design improvement rules

The case study demonstrates that standard production design improvement rules developed in the manufacturing industry can be transferred to the construction industry. Further, it is possible to develop new standard production design improvement rules derived from manufacturing best practice. For example, one such rule could be "minimise cutting". Cutting, like other subtractive production processes such as drilling, results in material wastage and tool wear.

As explained below, this rule could be applied successfully before, during and after construction. Figure 6.7 presents the potential production design improvement rule with three supporting design strategies which are now discussed.

Figure 6.8: Example of building design rule derived from manufacturing

Design rule	Design strategies
Minimise cutting	Match sizes of bespoke components and standard material sizes
	Harmonise the building's structural, envelope and internal grids
	Position internal fittings within the building's partitioning grids

This rule could be used before building construction to inform building designers how cutting by building component manufacturers could be reduced. For example, architects will often decide upon the finished width of external cladding panels for a building without consideration of the standard width of the sheet that they will be cut from. If an architect decides upon a panel width of 600 millimetres and the sheet width is 1200 millimetres only one panel width can be obtained per sheet. The sheet will be cut to a width of 650 millimetres, then bent over 25 millimetres on each side.

This results in considerable tool wear and material wastage (McLeod, 1999). If architects were to match the sizes of bespoke components to standard material sizes the production costs and times associated with tool wear and material wastage could be reduced. For example, if an architect decides upon a finished panel width of 550 millimetres, two panel widths could be cut from one sheet width. This would result in less cutting and radically reduced material wastage.

The rule could also be applied by building designers to minimise cutting during building construction. For example, cutting on-site can be significantly reduced if the sizes of structural, envelope and internal grids are harmonised. If these three grids are harmonised at 1.5 metres then floor and ceiling tiles do not have to be cut to infill around the internal perimeter. Further, building designers could use the rule to reduce cutting after the construction of the building. For example, cutting of partitions during tenant fit-out can be reduced if fittings, such as air conditioning outlets and ceiling lights, are positioned within the perimeters of partition grids during construction.

6.7.2 Transferability of production design evaluation metrics

No existing DFM metrics were found which could be transferred to the design of healthcare facility assisted bathrooms. The production design evaluation metrics developed in the case study comprise subjective expert judgements. Clearly, these metrics are not as objective as the metrics in existing DFM methodologies which have been established using work measurement techniques. However, as discussed in Chapter 4, developing production design evaluation metrics using work measurement can be expensive and time-consuming. For example, the development of work measurement based design metrics for assisted bathrooms would rely on several equal sized sample bathrooms being constructed using the various alternative methods available. Their construction would have to be observed and timed. Subsequently, the sample rooms would have to be dismantled and their contents disposed of. These types of costs are only recoverable if the metrics which are developed can be used repeatedly to inform and improve design decisions. When design is bespoke, there can be no certainty that the forms and finishes of any product, or the forms, finishes, configurations and interfaces of components, will ever be repeated. In these circumstances, the time and cost of developing work measurement based metrics may be wasted: a possibility unlikely to encourage investment in such metrics. Although mock-up rooms are quite often constructed for large and complex buildings, these are full-size sample which are used to refine construction details. These rooms are usually incorporated into the finished building to minimise their cost.

With uncertainty as to which, if any, organisation might be prepared to meet the cost of developing work measurement based metrics, subjective expert knowledge based metrics are a more economically viable alternative. However, for such metrics to have any validity they must comprise *an appropriate balance of all necessary expert knowledge*. In the case study, structured non-participant observation was used to determine whether the evaluation ratings comprised the knowledge of *all* those attending the meeting. A sample observation schedule is contained in Appendix J. It was recognised that if the meeting was dominated by one or two people (Fleming and Koppleman, 1996), or if groupthink prevailed (Green, 1998), the case study design evaluations would not reflect the considered opinions of all the ten experts attending the meeting. Further, it was realised that carrying out any task can be difficult when, as in this case, individuals work together for the first time (Laufer *et al*, 1996). In these situations, clashes of style (Johns, 1995) and a failure to focus on the task in hand (Greek, 1999) can often limit the contribution of some individuals.

For the purposes of observation, attendees' participation was defined as, "time spent focused on the design details, i.e. analysing, clarifying, developing, evaluating, explaining, listening, refining and/or selecting". Inter-observer agreement was measured by Cohen's Kappa as 0.87, which can be classified as "excellent" (Fliess, 1981). The full calculation of Cohen's Kappa is shown in Appendix J. Table 6.8 below, shows the level of participation by each attendee during all meeting periods.

Table 6.7: Mean participation by each attendee during all Meeting periods

Attendee	A	B	C	D	E	F	G	H	J	K
Participation	90%	88%	91%	66%	86%	86%	76%	37%	30%	72%

The pattern shown suggests that the meeting was of more interest to some attendees than others. However, this can be viewed as "normal", because whilst attendees A, B and C were involved in the major activities of screed and vinyl laying, attendees H and J were involved in the minor activities of electrical and equipment installation. H and J were present to make sure that no design

modifications were agreed which would have been detrimental to the electrical installations. Their presence at the meeting was necessary to ensure *an appropriate balance* of expert knowledge.

Table 6.9 below shows that overall participation was highest during the final meeting period when implementation actions were being agreed. This suggests that

Table 6.8: Mean participation by all attendees during each Meeting period

Meeting period	1	2	3	4	5
Mean participation by all attendees	76%	69%	73%	74%	88%

attention was keenest when the consequences of design modifications were being discussed. It is significant that during this final period no attendees suggested that the existing design should be retained. The levels of participation recorded by the attendees themselves on the form shown in Figure 6.1 correlated with the pattern observed by non-participants. The results of non-participation observation suggest that the evaluation ratings did represent the knowledge of *all* those attending the meeting. Further, it can be said that the evaluation ratings were formed by all *necessary* expert knowledge. This is because each organisation contributing to the design and construction of the assisted bathrooms was represented at the meeting. As was each organisation contributing to the design and production of the building components used. Although the production design evaluation metrics developed in the case study comprised *an appropriate balance of all necessary expert knowledge*, it is clear that the transferability of the metrics would be strengthened by additional evaluations carried out with similar groups of experts.

6.7.3 Transfer within Contractor-X

At a meeting held several months after the application of DFM principles there was unanimous agreement that further applications should be carried out. This meeting was attended by the healthcare facility's architect and Contractor-X's Site Office personnel. The Head Office personnel who had authorised the trial application of DFM principles were also present. This endorsement strengthens the case for transferability, particularly as Contractor-X operates globally with more than half of its turnover being generated outside of the UK.

6.8 Applying DFM Principles to Building Concept Designs

6.8.1 Introduction

Although the case study illustrates the successful application of DFM principles part-way through the design and construction of a building, DFM principles should first be applied at the concept design stage. It is at the concept design stage that existing DFM methodologies focus designers' efforts on the product as a whole. Firstly, to identify and eliminate components which are not essential to form or function. This reduces product development times, and cuts production times and costs, without reducing product functionality (Tibbetts, 1995). Secondly, to prevent components being designed which are individually easy to manufacture, but collectively difficult to assemble into a product. The research suggests that there are two major factors to be considered when seeking to apply DFM principles during concept design of buildings. These are discussed below.

6.8.2 Bills of materials, or an equivalent, for buildings

In the manufacturing industry, it is relatively straightforward to apply DFM methodologies to a whole product because product forms and finishes, and component quantities, forms, finishes, configurations and interfaces are fully defined by Bills of Materials (BoMs). As explained in Chapter 4, these computerised parts lists differ from Bills of Quantities used in building construction, in that they model and make explicit the exact interrelationships between every component. This means that the full implications of component modifications are immediately apparent during DFM application. For example, when the a design improvement rule such as "eliminate parts that act as conduits" is applied all the BoM entries relating to the affected conduit parts are immediately visible, and the materials from which they are manufactured are automatically identified.

The development of BoMs, or an equivalent, for buildings would assist the application of DFM principles to whole buildings. This is because buildings consist of many interdependent components (Winch, 1998), and changing component designs can have secondary and tertiary impacts (Slaughter, 2000). Thus, although component designs may be improved, the wider implications may be to the detriment of the overall building design.

The development and use of BoMs, or an equivalent, would involve many different construction organisations which use many different computer systems and software applications. This could lead to data capture and communication problems.

However, there are already initiatives which address the electronic representation of building and building component attributes. These include STEP (Standard for The Exchange of Product model data) and IAI (International Alliance for Interoperability).

STEP (ISO 10303) is a pan-industry international standard for the computer interoperable representation and exchange of product data. The objective is to provide a mechanism which is capable of describing product data independent from any particular computer system. The Building Construction sub-group of STEP is concerned with developing data exchange, sharing, and archival standards for the construction industry, in harmony with other industries. The IAI is a non-profit construction industry alliance which seeks to define, promote and publish a common language for information sharing across disciplines and technical applications. The work of the IAI is based on ISO 10303 and is focused on the definition, specification and electronic representation of all objects that occur within construction (Underwood *et al*, 2000). Their specifications, which are called Industry Foundation Classes (IFC), could potentially be used in the development of BoMs for buildings.

6.8.3 Building procurement arrangements

The case study involved suppliers, subcontractors and consultants meeting together part-way through a building's design. Suppliers, subcontractors and consultants meeting together during concept design is something which only some modes of building procurement will permit. Although these modes of procurement are widely recognised (Atkinson, 1998; Rideout, 1998), supplier and sub-contractor collaboration in concept design is still far less common than in the manufacturing industry (Gregory and Fan, 2000). However, although there are often differences between supply chains in construction and manufacturing, these differences are not fundamental and can be reduced (Anumba, 2000).

Moreover, supply chain differences should not prevent application of production design improvement rules and production design evaluation metrics provided they are standard. For example, as discussed in Chapter 4, standard DFM rules and metrics are applied during the design of many different types of manufactured goods. The procurement arrangements for different manufactured goods are not exactly the same, and not always fully collaborative (Sivadasan *et al*, 2000). Further, whilst the development of DFM rules and metrics may rely on collaborative working, their successful application does not rely on the same people working together again. Many different product designers, working in many different parts of the world, developing very different types of goods, have all used the same DFM rules and metrics with equal success.

Standard production design improvement rules and standard production design evaluation metrics need to be applicable irrespective of building type, client type or mode of procurement. Comprehensive and detailed instructions for all types of potential user would facilitate this. However, it is possible that a basic understanding of DFM principles would be carried into construction supply chains by those involved in early applications.

6.9 Chapter Conclusion

This chapter has described the case study designed to determine whether DFM principles can be successfully applied to buildings. In particular, the case study sought to determine how DFM principles could be applied where building designers have limited influence over component design; and whether DFM principles would be successful in improving construction productivity and quality where common DFM strategies, such as parts consolidation, can seldom be implemented.

An explanation of the research setting and research instruments has been provided and the events of the case study have been described in detail. Quantitative and qualitative results arising from the case study have been presented. Factors affecting transferability have been addressed, and the application of DFM principles during the concept design of buildings has been discussed. The principle findings of this part of the research are stated below.

It was demonstrated during the case study that existing DFM rules, modified DFM rules, and new standard production design improvement rules developed specifically for buildings and/or building components can be effective in improving the productivity and quality of building construction. It was also demonstrated that metrics based on subjective expert knowledge can be used to evaluate alternative building designs. These are a more economically viable alternative to metrics based on work measurement. It was explained that for such metrics to be valid they must comprise an appropriate balance of all necessary expert knowledge.

It was proposed that the development of BoMs, or an equivalent, for buildings would assist the application of DFM principles to whole buildings. This is because BoMs help designers see the affects of eliminating or modifying one component on all other parts, sub-assemblies and assemblies. Also, it was explained that standard production design improvement rules and standard production design evaluation metrics need to be applicable irrespective of building type, client type or mode of procurement. It was suggested that to make this possible they will need to be supported by comprehensive and detailed instructions.

Most significantly, the case study demonstrated that the application of DFM principles can be successful in improving the productivity and quality of building construction. The case study has provided an example where it has been both technically feasible and economically viable to apply DFM principles on a one-off construction project. This has been achieved where the building designers have limited influence over component design, and common DFM strategies, such as parts consolidation, could not be implemented.

In particular, an improved design has been developed and constructed for a fundamental healthcare requirement: assisted bathrooms. This design has generated construction cost savings of ten skilled operative days. Further, the case study demonstrated that application of DFM principles could lead to organisational business benefits, such as improved understanding of cost drivers, for construction project participants.

7.0 Development: DFM Strategies for the Construction Industry

7.1 Introduction

The results of the research reported in Chapter 5 and Chapter 6 suggest that DFM principles can be applied successfully to building components and buildings. However, research findings reported in Chapter 2 and Chapter 4 indicate that DFM principles for the construction industry do not currently exist. As a consequence, the development of DFM principles (standard production design improvement **rules** and standard production design evaluation **metrics**) will be required to facilitate their widespread application in the construction industry.

In this chapter, issues concerning the development of rules and metrics are explored. These are categorised as:

- classification issues;
- formulation issues;
- application issues; and
- success issues.

Then, strategies are proposed for achieving successful application of rules and metrics throughout the construction industry. Individual strategic plans are presented for specific types of construction organisations. These are validated through structured interviews conducted with senior industry practitioners.

7.2 Classification Issues

7.2.1 Introduction

It was explained in Chapter 4 that different rules and metrics are applicable to different component levels, and can improve different phases of production. For example, existing DFM metrics can be used to evaluate the manufacturing times for alternative designs of a discrete engineered building component. However, these metrics can not be used to evaluate the construction times for alternative designs of an entire building.

In this section, a classification system for rules and metrics is proposed. This is required to facilitate the formulation of effective rules and metrics by different types of construction organisations. A nomenclature for building components levels and building production phases provides the structure for the classification of rules and metrics.

7.2.2 A nomenclature for components and processes

Figure 7.1 shows a coded hierarchy of four building component levels which span from raw materials to entire buildings. This coded hierarchy is not exhaustive, but provides sufficient detail for the taxonomy of rules and metrics which will be introduced in the next sub-section. The examples shown in Figure 7.1 are derived from the case study reported in Chapter 6.

Figure 7.1: Building component levels

Component levels			Example
↑	C0	Product	*Healthcare facility*
	C1	Assembly	*Assisted bathroom*
	C2	Sub-assembly	*Shower area*
	C3	Part Formed material Formless material	*Shower unit* *Vinyl floor and wall covering* *Sealant*
	C4	Raw material	*Bauxite* *Polyvinyl chloride* *Acrylic*

Figure 7.2 shows a coded hierarchy of building production phases. Again, this hierarchy provides sufficient detail for the taxonomy of rules and metrics.

Figure 7.2: Building production phases

Production phase				Example
↑	Building construction	P0	Building Construction	*Forming interfaces*
				Constructing assemblies
				Enabling works
		P1	Component Placement /Installation	*Installing assemblies*
				Installing parts
				Placing materials
	Building component production	P2	Component Assembly	*Prefabricating assemblies*
				Prefabricating sub-assemblies
				Assembling parts
		P3	Component Manufacture	*Producing parts*
				Processing formed materials
				Processing formless materials

Applying rules and metrics to different building component levels can improve the productivity and quality of one or more building production phases. Building component manufacture can be regarded as the first production phase, followed by building component assembly, building component installation and building construction.

Figure 7.3 shows a coded hierarchy of the production process levels which occur during building production phases. Elementary *motions*, such as picking up

Figure 7.3: Production process levels

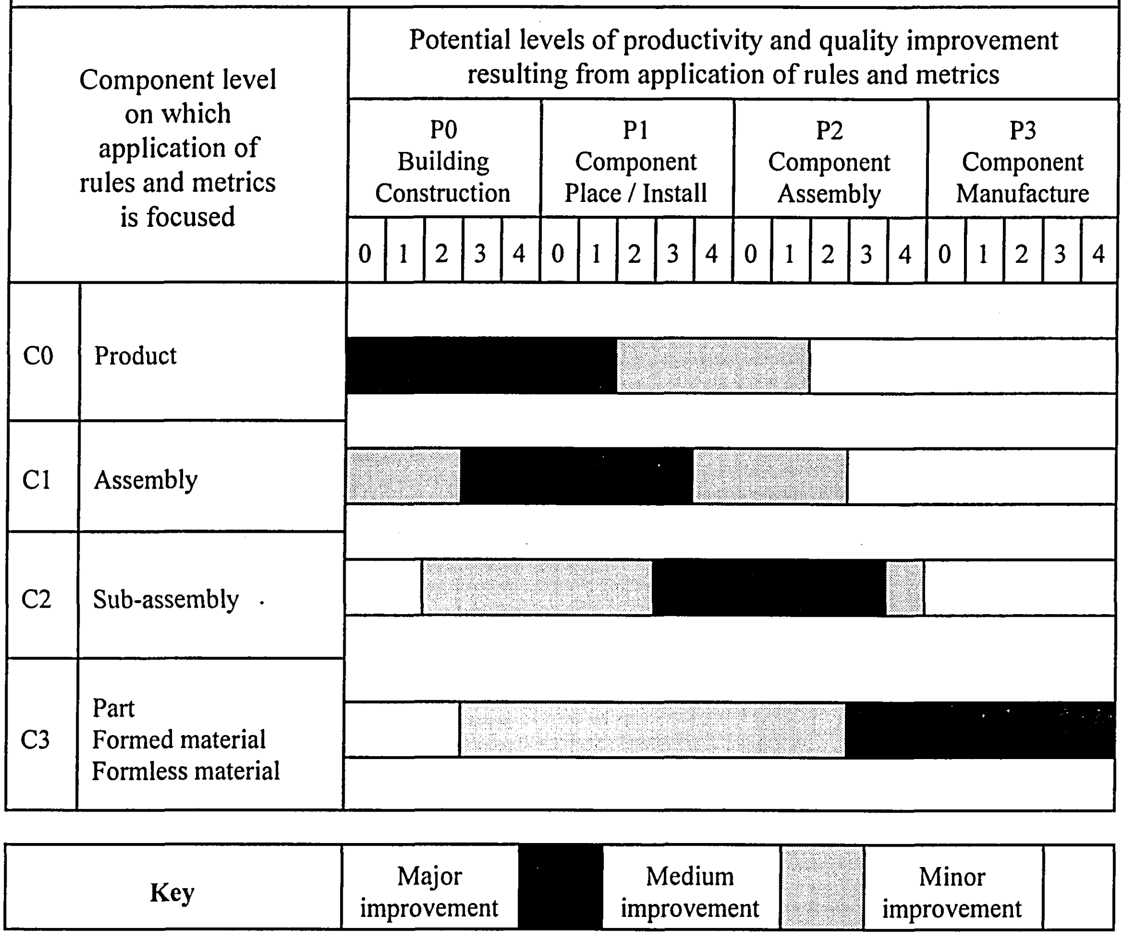
Process levels			Example	
	0	Process	*A sequence of operations,*	*e.g. construct groundworks*
	1	Operation	*A sequence of tasks,*	*e.g. lay drainage*
↑	2	Task	*A sequence of activities,*	*e.g. dig a drainage trench*
	3	Activity	*A sequence of motions,*	*e.g. set out a drainage trench*
	4	Motion		*e.g. picking up a hammer*

a hammer, are the first production process level. These can be aggregated into *activities*, such as marking out a trench. This *activity* would include *motions* such as picking up a hammer, knocking a setting out peg into the ground with the hammer, and so on. Setting out a trench is just one of the *activities* involved in the *task* of digging a drainage trench. Others would be scraping off topsoil, removing soil from site in lorries etc.

Digging a trench is one of the many *tasks* which have to be completed when carrying out the *operation* of laying the drainage for a building. Other *tasks* include placing gravel to falls in the trench, placing the drainage pipes on the gravel, jointing pipes, and covering pipes with stone before backfilling the trench. The *process* of constructing groundworks for a building comprises several *operations*. These include site clearance, laying drains, installing services, placing kerbs and tarmacing roads.

Figure 7.4 illustrates the potential productivity and quality improvements which could result from applying rules and metrics to specific levels of building components. The codes introduced in the preceding three figures are used.

Figure 7.4: Potential levels of productivity and quality improvements



For example, application of rules and metrics at component level C0 are shown to have most impact on building production phases P0.0 to P1.1. That is, rules and metrics which are formulated for application to the design of entire buildings are shown to have most affect on the production phases from building construction *processes* to building component placing / installing *operations*. Rules and metrics which are formulated for application to level C0 are shown to have least impact on phases from component assembly *tasks* to component manufacture *motions*.

In contrast, rules and metrics which are formulated for application to level C3, parts, formed materials and formless materials, are shown to have least affect on building construction *processes*, *operations* and *tasks*. For example, a rule such as, "use pilot screws to avoid cross threading", may result in major productivity and quality improvement to some component manufacture *processes*. However, it is only likely to result in minor improvement to building construction *processes* such as using a tower crane to lift an air conditioning plant on to a roof structure. The air conditioning plant may be more robust because none of the screws used in its manufacture and assembly have cross threaded, but that is unlikely to reduce the time and cost of lifting the air conditioning plant into position.

Other rules, such as "reduce component count and component types", could be applied to several component levels. For example, designers could seek to reduce the component count and component types of entire buildings (C0), building assemblies (C1) and/or building sub-assemblies (C2). As shown in Figure 7.4, application to these three component levels could result in major productivity and quality improvements in building production phases from building construction *processes* (P1.0) to building component assembly *activities* (P2.3).

7.2.3 A classification system for rules and metrics

Using the nomenclature introduced above, a classification system for rules and metrics is now described.

Figure 7.5 shows a taxonomy for standard production design improvement rules. This taxonomy classifies rules by the building component level which their application is focused on. Further, it highlights in which building production phases rules are likely to be most effective. As discussed above, some rules are applicable to more than one component level.

Figure 7.5: Taxonomy of standard production design improvement rules for buildings

Application focus		Examples of standard production design improvement rules	Success focus
C0	Product	*Reduce component count and component types*	Building production phases P0.0 to P1.1
		Match component properties and process characteristics	
		Strive to optimise balance between accuracy and tolerances	
C1	Assembly	*Reduce component count and component types*	Building production phases P0.3 to P1.3
		Strive to minimise cutting before, during and after construction	
		Ensure adequate access and unrestricted vision	
C2	Sub-assembly	*Reduce component count and component types*	Building production phases P1.3 to P2.3
		Design sub-assemblies that cannot be constructed incorrectly	
		Strive to eliminate adjustments	
C3	Part Formed material Formless material	*Design components that cannot be placed / installed incorrectly*	Building production phases P2.3 to P3.4
		Design components to be self-aligning and self-locating	
		Ensure the ease of handling of components from bulk	

Figure 7.6 shows a taxonomy for standard production design evaluation metrics. This taxonomy classifies metrics by the building component level which their application is focused on. Further, it highlights the building production phases for which metrics should provide data.

Figure 7.6: Taxonomy of standard production design evaluation metrics for buildings

Application focus		Examples of standard production design evaluation metrics	Success focus
C0	Product	*Expert knowledge comparisons of alternative product designs*	Building production phases P0.0 to P1.1
		Attribute comparisons for alternative assemblies	
		Alternative building construction times as determined by different design features	
C1	Assembly	*Expert knowledge comparisons of alternative assembly designs*	Building production phases P0.3 to P1.3
		Attribute comparisons for alternative sub-assemblies	
		Alternative component placing / installation times as determined by different design features	
C2	Sub-assembly	*Expert knowledge comparisons of alternative sub-assembly designs*	Building production phases P1.3 to P2.3
		Attribute comparisons for alternative formless materials, formed materials and parts	
		Alternative component assembly times as determined by different design features	
C3	Part Formed material Formless material	*Alternative component manufacturing times as determined by different design features*	Building production phases P2.3 to P3.4
		Performance comparisons for alternative production processes	
		Cost comparisons for alternative raw materials	

Five types of standard production design evaluation metrics are shown. The first of these, expert knowledge comparisons of alternative designs, was introduced Chapter 6. This type of metric was generated for healthcare facility assisted bathrooms during the case study carried out with Contractor-X.

Attribute comparisons of alternative components were described in section 3 of Chapter 4. In existing DFM methodologies, these types of metrics are used to compare factors, such as the number of fasteners found in common component types. These factors often have a direct affect on production times and costs.

Alternative production times as determined by different design features were also described in section 3 of Chapter 4. In existing DFM methodologies, standard production times are linked to a wide range common component features, such as "parts severely nest or tangle". This type of metric was generated for the bespoke goods produced by Supplier-Y during the action research intervention reported in Chapter 5. Their metrics are linked to design features such as the geometry of hinges etc.

Performance comparisons for alternative production processes, and cost comparisons for alternative raw materials were also described in section 3 of Chapter 4. Typical metrics include setup times for alternative processes and cost per kilogram for alternative materials.

The purpose of the classification system shown above is to provide a generic structure for the formulation of effective rules and metrics by construction organisations. During the interviews with industry practitioners reported later in this chapter, the system was thought simple to understand and fit for purpose.

7.3 Formulation Issues

7.3.1 Introduction

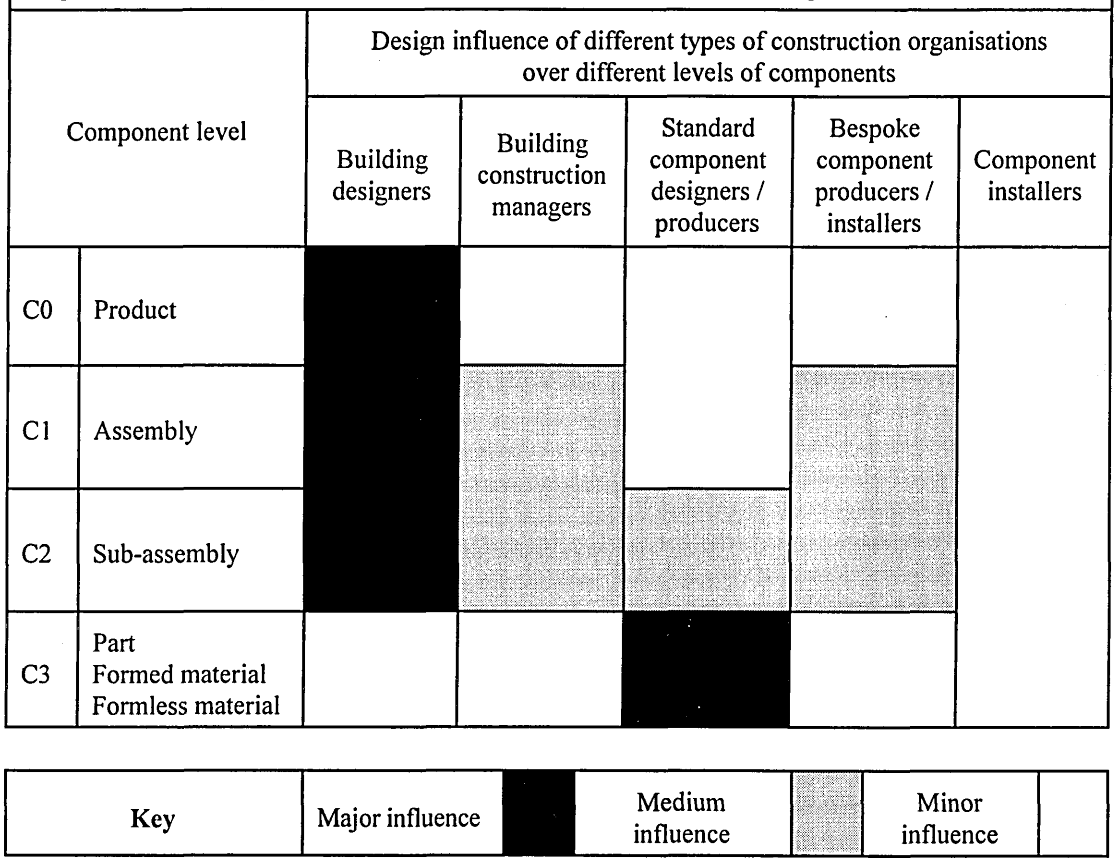
It was explained in Chapter 4 that existing DFM rules and metrics have limited relevance to building components and buildings. As a consequence, it will be necessary for new standard production design improvement rules and standard production design evaluation metrics to be formulated.

The research reported in Chapters 5 and 6, suggests that the formulation of effective rules and metrics for building components and buildings is technically feasible and economically viable. However, the research also highlights that different rules and metrics are required by different types of construction organisations. This is because different types of organisations have design influence over different building component levels.

7.3.2 Design influence

Figure 7.7 below shows the relative design influence of different organisations working in the construction industry. The range and classification of organisations which is shown in the following figures was thought to be comprehensive and valid by interviewees when verification was sought.

Figure 7.7: Design influence of different construction organisations



Building designers are shown to have major influence over component levels C0: buildings, C1: building assemblies, and C2: building sub-assemblies. In building design, architects often focus on building form, whilst engineers tend to focus on building structure and equipment. Both are concerned with having their designs successfully realised during building component production and building construction.

Construction managers, such a Contractor-X, are shown as having medium influence over component levels C1: building assemblies, and C2: building sub-assemblies. Their design input focuses on building production. As described in Chapter 4, during the course of building construction, the construction managers call and chair meetings to "sort out" building designs. Bespoke component producers / installers attend these meetings, and with building designers and construction managers, they seek to develop production details for building assemblies and sub-assemblies without compromising building form and function. Hence, in Figure 7.7, bespoke component producers / installers, such as Supplier-Y, are also shown to have medium design influence over component levels C1 and C2.

In contrast, standard component designers / producers, do have the major influence over the design of the formless materials, formed materials and parts which they offer. Also, as bespoke building sub-assemblies are often produced from these standard materials and parts, they have a medium design influence over building sub-assemblies. This design influence is often passive, with their standard materials and parts being selected from catalogues by building designers and/or bespoke component producers / installers. However, standard component designers / producers may also be invited by construction managers to attend meetings to "sort out" building sub-assembly designs.

In Figure 7.7, component installers are shown as having only minor design influence. This type of "labour only" organisation includes itinerant carpenters, gangs of bricklayers, teams of steel erectors etc. There may be some occasions where these types of construction operatives may have a minor design influence. For example, steel erectors may be asked for their opinion about the design of beam to column connection plates by manufacturers. However, their design influence is far less than the other four types of organisations.

When seeking to successfully apply DFM principles, construction organisations should initially formulate rules and metrics for application to the component levels which they have most influence over. This is because, as discussed in Chapter 4, there are costs involved in formulation, and these costs will not be recovered if the rules and metrics can not be applied successfully. Further, the research reported in Chapters 5 and 6, suggests that rules and metrics have to be seen as directly relevant within the organisation for formulation to be achieved. After an organisation has formulated rules and metrics which are perceived as being directly relevant, it may then be possible to progress onto rules and metrics which deal with interfaces with other organisations' outputs.

Having identified the component levels which construction organisations have influence over, the types of rules and metrics that different organisations should formulate are now proposed.

7.3.3 Formulation of rules and metrics

Figure 7.8 shows which types of rules and metrics different types of construction organisations should seek to formulate. Existing DFM rules and metrics are included in Figure 7.8 because, as discussed in Chapter 4, it is possible for them to be applied successfully by some businesses in the construction industry. Also, modified DFM rules are included. This is because as discussed in Chapter 6, existing DFM rules, such as, "design parts which cannot be installed incorrectly", can be successfully modified for application in the construction industry.

Figure 7.8: Relevance of different types of rules and metrics to different types of construction organisations

Different types of rules and metrics		Relevance to different types of construction organisations				
		Building designers	Construction managers	Standard component designers / producers	Bespoke component producers / installers	Component installers
Standard production design improvement rules	Existing DFM rules	Medium	Minor	Major	Medium	Minor
	Modified DFM rules	Medium	Medium	Major	Medium	Medium
	New rules	Major	Medium	Major	Medium	Medium
Standard production design evaluation metrics	Existing DFM metrics	Minor	Minor	Medium	Minor	Minor
	New work measurement metrics	Medium	Medium	Major	Medium	Medium
	Expert knowledge metrics	Medium	Medium	Minor	Medium	Minor

Key	Major relevance	(black)	Medium relevance	(grey)	Minor relevance	(white)

As discussed in Chapter 4, DFM rules and modified DFM rules are of major relevance to standard component designers / producers. In contrast, they are of only medium or minor relevance for other types of organisations. This is because much building production and building construction involves production processes which are very different to those addressed by existing DFM rules. For example, the DFM rule, "maximise part symmetry to ease handling" has little relevance to construction activities such as pouring concrete into a foundation trench or applying paint to a wall. Further, as explained in section 5 of Chapter 4, existing DFM rules could possibly be applied to those standard and custom buildings which are mainly factory produced. However, these types of buildings are designed by their producers. Consequently, existing DFM rules are not shown as being of major relevance to building designers.

New rules are of major relevance to building designers and standard component designers / producers. This is because these are the organisations which have most design influence in the construction industry, and, unlike existing rules, the effectiveness of new rules would not be limited to production processes which are similar to those found in the manufacturing industry. New rules could be formulated by each organisation internally. As described in section 4 of Chapter 5, the knowledge of how to design for production can already be contained within construction organisations. In these situations, the formulation of rules is the documentation, agreement, structuring and codification of what is already known in the organisation to be the best way to design for production.

In some cases, buildings designers could have the knowledge to formulate rules which address the construction of entire buildings. However, as described in section 6 of Chapter 5, component producers seldom have this breath of knowledge. Their understanding is often limited to how interfacing components and processes can damage their own components. Consequently, component producers would benefit from access to supplementary standard production design improvement rules which address wider building construction issues. As discussed in Chapter 6, this approach may not prove to be as effective as having product designers, with the aid of BoMs, take the lead in the design of components to make overall product assembly simpler. Nevertheless, supplementary rules would offer a way of eliminating the design of building components which could make overall building construction more difficult. Further, the success of this approach does not depend on any change to the relationship between building designers and designers of building components. Neither, it does it depend on the introduction of BoMs for buildings.

Existing DFM metrics are relevant to some standard building components. For example, as described in Chapter 2, existing DFM metrics have been successfully applied to shower heater units. These are discrete engineered components. However, there are many other standard building components, such as bricks, plasterboards, etc, which do not lend themselves to the application of existing DFM metrics. Compared with the manufactured goods to which DFM has been successfully applied, these components use quite different materials and processes. Consequently, existing DFM metrics are of medium relevance to standard component designers / producers. They are shown as being of minor relevance to other organisations because of their limited applicability to most production processes in the construction industry.

New work measurement metrics are shown as being of medium relevance to all five types of organisations. BS 3138: 1979 defines work measurement as "the application of techniques designed to establish the time for a qualified worker to carry out a specified job at a defined level of performance". It was explained in section 3 of Chapter 4 that existing DFM metrics link work measurement data to common component design features, thus enabling designers to determine how their decisions will affect production times.

Work measurement is recognised within the construction industry. For example, the standard text book, Construction Site Studies (Forster, 1989) identifies work measurement as a means of, "determining the length of time each job should take by an average worker". However, work measurement data is not widely used in the construction industry to assess the consequences of design decisions.

It is technically feasible for construction organisations to develop their own work measurement data, and practical advice has been available from the Chartered Institute of Building for many years (CIOB, 1985). However, as discussed in Chapter 4 and demonstrated in Chapter 5, the development of work measurement data is costly and will not always be economically viable. This is why new work measurement metrics are shown as being of only medium relevance.

An alternative to work measurement metrics is expert knowledge metrics. An example of they can be generated was provided in Chapter 6. Expert knowledge metrics are shown as being of medium relevance to building designers, construction managers and bespoke component producers / installers. Building designers could instigate the generation of these metrics with construction managers and component producers / installers "on-line" during the many on-site design meetings which are called to "sort out" designs. Also, they could seek to generate these metrics "off-line" at their offices. In either case, the meeting format which was used in the case study with Contractor-X could be adopted.

As discussed in section 7 of Chapter 6, this type of metric does not offer the accuracy of work measurement data. However, DFM metrics do not depend on total accuracy for their success. Their success depends on the comparison of the production times for alternative designs which they provide (Westport, 1999). Furthermore, the traditional cost measurements based on bills of quantity which are universally accepted in the construction industry are seldom entirely accurate (Flannagan and Tate, 1997).

Expert knowledge metrics are shown as being of minor relevance for standard component designers / producers because these organisations have sufficient repetition of pre-order design certainty to make the generation of work measurement metrics economically viable. Similarly, component installers have sufficient repetition of motions, activities and tasks to make the generation of new work measurement metrics economically viable. For example, a gang of bricklayers does little else other than lay bricks and blocks, and point up the mortar joints between them. If a large labour only firm of bricklayers has the opportunity to advise a building designer that one brickwork feature will take longer to construct than another, they could generate and aggregate the work measurement metrics necessary to do this.

7.4 Application Issues

7.4.1 Introduction

Different application methods for rules and metrics are possible for different construction organisations. Design authority and design certainty are the two key factors which determine what methods are technically feasible and economically viable for each organisation.

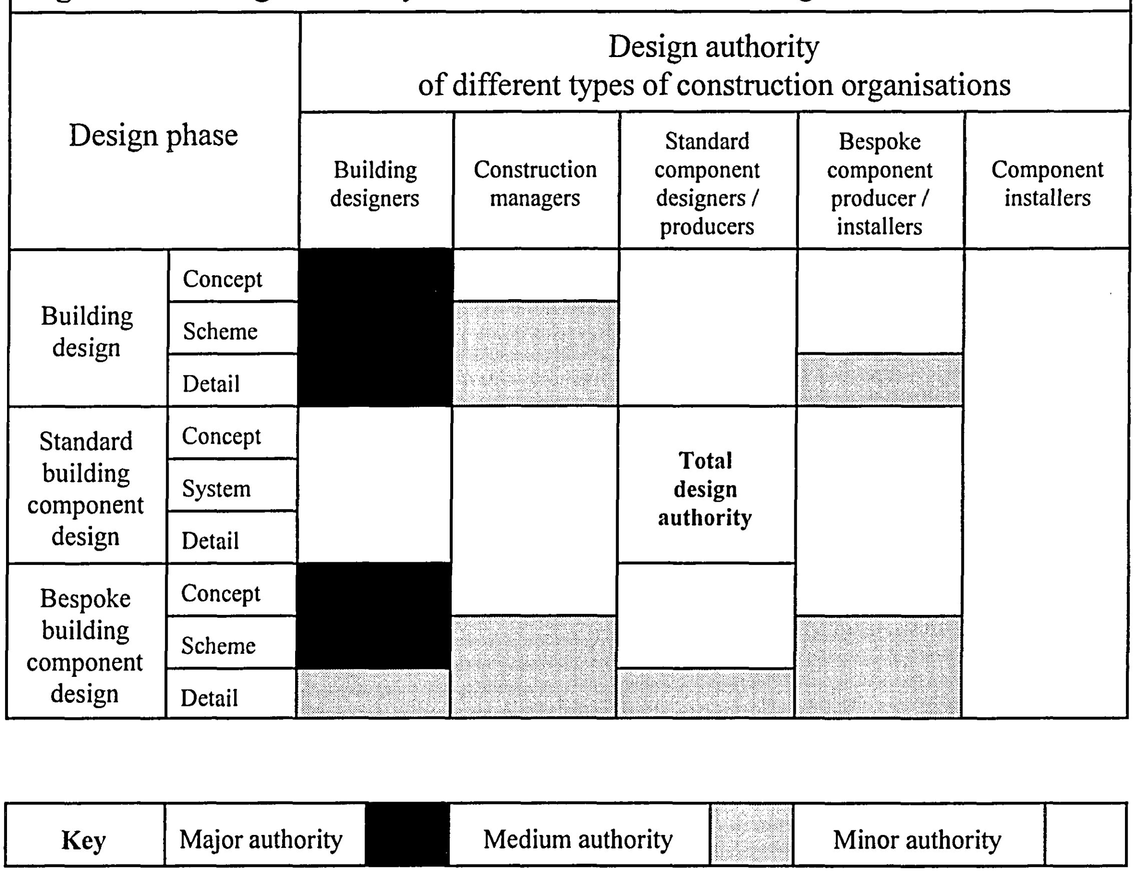
As explained in detail in section 5 of Chapter 2, it is the timing of design certainty which determines what information systems are technically feasible. Further, it is the frequency of design certainty repetition which determines what information systems are economically viable. For example, a car marketing / assembly company such as Honda achieves a very high repetition of pre-order design certainty. Consequently, it is highly feasible and viable for them to invest in Bills of Materials for cars. In the construction industry, where there is no repetition of post-production design certainty, it is neither feasible nor viable to invest in Bills of Materials for buildings.

Design authority indirectly determines what design information systems are feasible and viable. This is because the more design authority an organisation has, the more control it has over the timing and repetition of design certainty. For example, Honda have a high repetition of pre-order design certainty because they able to dictate product design to their customers.

7.4.2 Design authority

Figure 7.9 shows the relative authority of different construction organisations during building component design and building design.

Figure 7.9: Design authority of different construction organisations



In the construction industry, only standard component designers / producers have total authority over all the design phases for the components which they offer to the market. Provided they adhere to statutory requirements, standard component designers / producers are able to dictate design to their customers through a range of standard options.

It was also explained in Chapter 2 that building design is often customer-led and location-specific. Where this is the case, building designers are constrained by the instructions of their clients and Planning Officers. These factors mean that, whilst building designers have more design authority than construction managers, bespoke component producers / installers, and component installers, they do not have total design authority. Nevertheless, they have major design authority over all phases of building design, and over the concept and scheme phases of bespoke component design.

The design authority of construction managers and producers of bespoke components can vary within the parameters shown in Figure 7.9 depending on the mode of building procurement which is used. Although there are various procurement systems, they can be divided into two broad categories: "traditional" and "non-traditional". With traditional methods, design and construction are seen as separate and sequential processes. In contrast, non-traditional methods seek to integrate design and construction. With non-traditional methods, construction managers and producers of bespoke components are appointed earlier, and sometimes have more authority in the design process. However, although non-traditional methods became popular in the 1980's, their use has declined in recent years, leaving traditional modes of procurement as the most frequently used (Ashworth and Hogg, 2000).

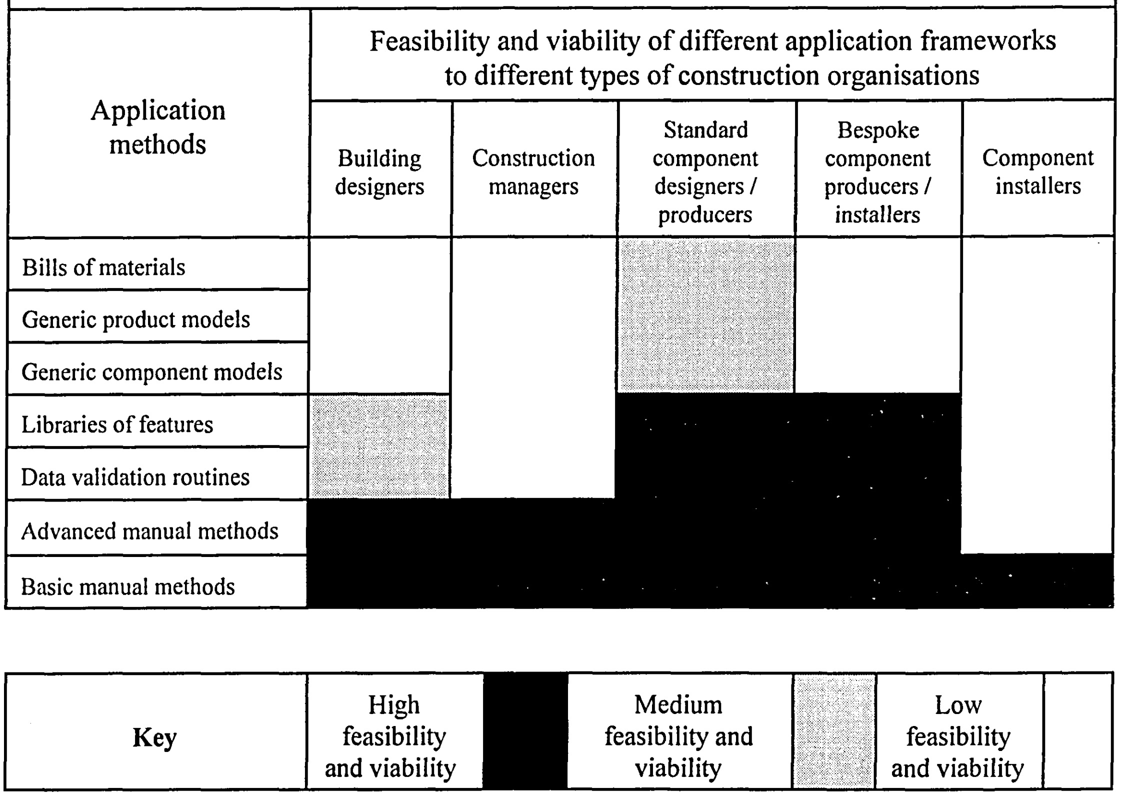
Another factor which can affect the design authority of construction managers and producers of bespoke components is the types of supply chain arrangements in which they are involved. In recent years, there has been an interest in partnering in the construction industry (Bennet and Jayes, 1998). This has resulted in clients having preferred building designers, building designers having preferred construction managers and construction managers having preferred producers of bespoke components. With these types of supply chain arrangements, traditional methods of procurement may be used, but the construction managers and producers of bespoke components are prepared to contribute to the early stages of building design because they know that they will be appointed to carry out production work after the completion of the design. However, partnering has had limited success in the construction industry and one-off transactional supply chain arrangements are still the most frequently used (Smit, 1997).

Component installers are shown to have only minor authority. This is because it is in only very unusual circumstances that they can dictate the outcome of a design decision. If the nature of an installation is very specialised and extremely dangerous, for example it is to be carried out at great height, their advice may be sought and given particular weight. However, actual design decision would be made by others.

7.4.3 Application methods for rules and metrics

Figure 7.10 shows the application methods which are technically feasible and economically viable for different construction organisations.

Figure 7.10: Feasibility and viability of different application methods for different types of construction organisation



As discussed above, the feasibility and viability of an application method is determined by design authority and design certainty. For example, standard component designers / producers have sufficient design authority to dictate design to their customers through a range of standard options. This means they have a high repetition of pre-order design certainty. As a result, it is highly feasible and viable for this type of organisation to apply standard production design improvement rules and standard production design evaluation metrics. They can use manual methods, such as checklists of rules and charts containing metrics to do this. Alternatively, or subsequently, they could develop more advanced manual methods comprising workbooks and manuals. Further, it is feasible and viable for this type of organisation to embed rules and metrics into design software as data validation routines. It is also possible for this type of organisation to develop libraries of standard component features which have been designed using rules and metrics. These libraries of features could be used in future component designs. This approach of designing using rules and metrics, then capturing designs for future customisation, could be extended to generic component models and generic production models. Furthermore, standard component designers / producers can capture designs, generated with the aid of rules and metrics, within Bills of Materials.

In contrast, for component installers, only basic manual methods are feasible, but even these could be useful. It is not in the interest of labour only component installers to have to achieve designs on-site which do not consider installation issues. This is likely to affect their productivity and, therefore, their earnings. Consequently, if they can produce a checklist of installation best practice criteria for consideration by building designers, even this rudimentary measure could result in better design for installation.

Basic and advanced manual methods are feasible and viable for bespoke component producers / installers. However, as described in Chapter 5, once data validation routines and libraries of features have been developed they are far quicker to operate and require less diligence for successful application. Unlike standard component designers / producers, it is not economically viable for this type of organisation to capture designs, developed with rules and metrics, as generic models or Bills of Materials.

Only manual methods are technically feasible for construction management organisations. This is because, whilst they have sufficient design authority to drive the modification of building designs and bespoke building component designs, they do not actually generate any design or production information. Therefore, they can only check the outputs of building designers and bespoke component producers / installers and guide subsequent improvement. Manual methods are also suitable for building designers. However, for building designers who repeatedly design similar sub-assemblies, it may also be possible to embed rules and metrics into their design software as data validation routines. Further, it may be possible for them to develop libraries of standard component features which are designed using rules and metrics.

7.5 Success Issues

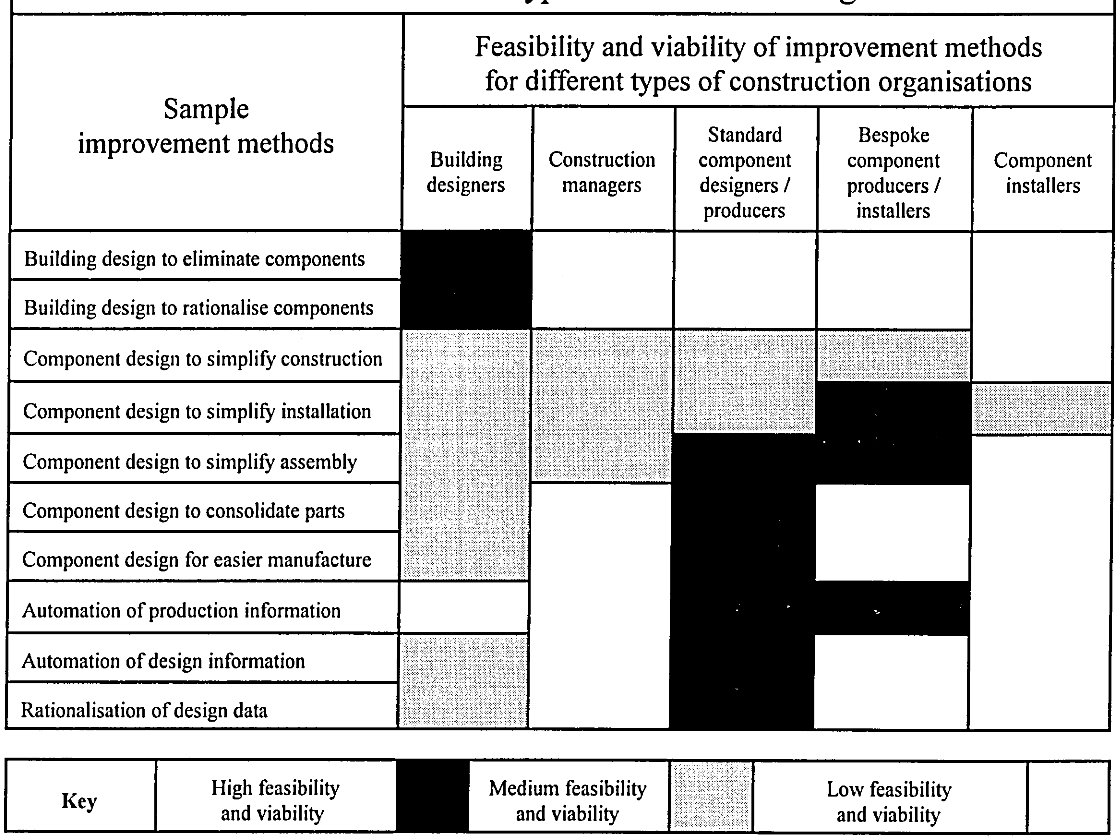
7.5.1 Introduction

It was explained in detail in Chapter 2 that the timing and repetition of design certainty determines what production processes are technically feasible and economically viable. It was explained in Chapter 4 that many DFM success strategies depend on high repetition of pre-order design certainty. Further, it was argued that because building design is often customer-led and location-specific, many DFM success strategies are neither feasible nor viable for construction organisations. These issues were explored in more detail during the action research intervention described in Chapter 5. For example, parts consolidation is seldom feasible for Supplier-Y and, even when it is, it would not necessarily reduce installation times or improve installation quality. Also, it would not reduce inventories because producers of bespoke components have no need to hold inventories. These findings highlight that applying rules and metrics during design does not guarantee improved productivity and quality during production. Rules and metrics must focus efforts on improvement methods that are feasible and viable.

7.5.2 Productivity and quality improvement methods

Figure 7.11 shows the feasibility and viability of various productivity / quality improvement methods for different types of construction organisations.

Figure 7.11: Feasibility and viability of productivity / quality improvement methods for different types of construction organisation



Standard component designers / producers are shown to have most opportunity to achieve productivity and quality improvements through the application of rules and metrics. As explained in detail in section 5 of Chapter 2, this is because they have a high repetition of pre-order design certainty. This means it is both feasible and viable for them to design their components for ease of manufacture, consolidation of parts and simple assembly. Also, because they have total design authority, they can rationalise and automate their design and production data.

It is also shown that it is feasible and viable for standard component designers / producers to design for simple installation and construction. However, for them to achieve this they would have to include component installers and construction managers in the development of their rules and metrics, and it is likely that their involvement would be on a fee paying basis. Consequently, a lower level of feasibility and viability is shown for these two methods.

Only three methods are shown as being highly feasible and viable for bespoke component producers / installers. These are the automation of production information, design to simplify component assembly and design to simplify component installation. In addition, design to simplify construction is shown as being of medium feasibility and viability. However, once again this would rely on the inclusion of construction managers.

As demonstrated in the action research intervention, and discussed above, many DFM success strategies are not relevant to producers / installers of bespoke building components. For example, component interchangeability is likely to be restricted above the level C3, which means that two major strategies for quality and productivity improvement, parts consolidation and assembly automation, are of limited usefulness. However, although there are few opportunities for component standardisation, there are considerable opportunities for data standardisation and automation. This is because the times and costs of modifying existing data are often lower than the times and costs of writing new data. For example, if a customer changes one product dimension it may take hours to modify affected sub-assemblies if they have already been produced, but only a few minutes to amend relevant generic drawings and/or bills of materials. As described in section 5 of Chapter 5, reuse of data results in radical reductions to administration times, which reduces the compression of the time available for production This, in turn, results in production operatives not having to rush their tasks and/or work long hours of unproductive overtime. These two factors can make a significant contribution to improving product quality and reducing the costs of reworking.

Three methods are shown as being of medium feasibility and viability for construction management organisations. These are component design to simplify assembly, component design to simplify installation and component design to simplify construction. Opportunities for this type of organisation are limited because they do not produce anything. However, as discussed above, they have experience of building construction, building component placing / installation and building component assembly, which could help improve productivity and quality in the construction industry. If this experience can be documented, rationalised, agreed, structured, codified and then brought to bear during design it could result in better performance by producers and installers.

Only one method is shown as being feasible and viable for component installers. This is component design to simplify installation. Again, if they could furnish designers with their knowledge in the form of rules and metrics, this could result in components which are easier to install.

Building designers are shown to be the type of construction organisation with the most opportunities to improve productivity and quality. Building design to eliminate components and to rationalise components is shown to be highly feasible and viable for them. All other methods, other than automation of production information are shown to have medium feasibility and viability. However, as discussed above, the influence of building designers is limited to bespoke building components. Therefore, the five component design improvement strategies do not relate to standard parts, standard formed materials and standard formless materials.

7.5.3 Defining success

As discussed above, being able to formulate and apply rules and metrics should not be confused with successful transfer of DFM principles into the construction industry. The success of DFM principles should be measured in terms of improved productivity and quality. Figure 7.12 outlines how the success of DFM in the manufacturing industry has developed over many years.

Figure 7.12: Development of DFM from a design idea to a design imperative	
1940's - 1970's	*Improving the economics of manufacture through design became an increasingly widely recognised, but largely unachieved, product design idea*
1970's - 1980's	*Introduction of the first DFM methodologies enabled industrial and engineering designers to improve the manufacturability of products*
1980's - 1990's	*Introduction of DFM rule / metric methodologies directed user companies to invest in more efficient manufacturing processes and materials*
1990's -	*The remarkable improvements in productivity and quality achieved by users of DFM led to it becoming a product design imperative for many companies*

The survey findings reported in Chapter 2 and Chapter 4 indicate that design in the construction industry is currently similar to design in the manufacturing industry before the introduction of the first DFM methodologies in the 1970's. That is, as shown in Figure 7.12, improving the economics of construction through design is a widely recognised, but largely unachieved, concept.

The findings of the deductive research reported in Chapters 5 and Chapter 6 indicate that the introduction of DFM principles would have similar results to the introduction of the first DFM methodologies in the manufacturing industry. That is, improvements in productivity and quality would probably be significant rather than remarkable.

However, it cannot be assumed that significant improvements will be achieved. The introduction of new practices into construction organisations can be a slow process (RICS, 1995) which is unlikely to be successful without planning (Anderson *et al*, 1999). Practical strategic plans are required if construction organisations are to formulate and apply rules and metrics successfully. Individual strategic plans for specific types of construction organisation are now proposed.

7.6 Strategies for Successful Application of DFM Principles

7.6.1 Background

In this section, an individual strategic plan for each of the following types of construction organisations is presented:

- building designers;
- construction managers;
- standard building component designers / producers;
- bespoke building component producers / installers;
- labour only component installers.

As described in Chapter 3, each strategic plan was presented to industry practitioners during structured interviews carried out in a group meeting held at the offices of one of the participants. A thorough explanation of the plans, based on the figures contained in the preceding sections of this chapter, was provided for the interviewees. The interviews involved a purposive sample of seven participants. Two are building designers, two are construction managers, and three are employed by companies which design, manufacture, supply and/or place or install building components. This sample comprised representatives from organisations which have been trying, without success, to implement DFM. None of the sample had participated in earlier research by the author.

These organisations had tried to implement DFM because of pressure from the multi-national building client which provides them with the majority of their financial turnover. Their client is aware of the production improvements achieved as a result of DFM application in the manufacturing industry, and wishes to see similar improvements in the construction of its buildings. The organisations had become aware of the author's knowledge of DFM through his publications in professional journals, and welcomed the opportunity to review his strategies for successful application of DFM principles. Twelve representatives from the different organisations were invited to review the strategies, and seven of these directors and senior managers were able to attend.

During initial discussions with the interviewees, it became apparent that they shared several fundamental misconceptions which had impeded their implementation of DFM. For example, interviewees expressed concern about "knowing where to start". They felt that the few examples of productivity and quality improvements provided by their client offered little insight into who should apply DFM. Building designers felt that DFM had little to do with them, whereas other interviewees felt that DFM was the domain of designers.

Also, the interviewees suspected that DFM was something to do with increasing the standardisation of designs in order to achieve economies of scale during production. As a result of this misconception, one building designer regarded the client as being "confused" when advocating the implementation of DFM, whilst still wanting unique buildings. Further, interviewees assumed that DFM meant trying to organise building production so it could be carried out in factories. This assumption had undermined the perceived value of DFM to the interviewees, because they were frequently involved in the factory production of building components. Consequently, DFM sounded like "reinventing the wheel" to them. Although they had considerable doubts about the relevance of DFM to their activities, the interviewees believed that their client would not relent in demanding productivity and quality improvements. Further, they believed that the client would not stop criticising them for their failure to implement DFM. Consequently, the interviewees welcomed the opportunity to assess the technical feasibility and economic viability of strategic plans for the successful application of DFM principles. A sample interview schedule, together with a description of factors considered during its design are provided in Appendix K.

The content of the strategic plans is derived from the foregoing analysis of key development issues. Each strategic plan comprises four parts listed below.

1. Strategic goal.
2. Application issues.
3. Formulation issues.
4. Success issues.

None of the strategic plans rely major technical or organisational innovations. In particular, they do not depend on the development of BoMs for buildings or the adoption of supply chain partnering. Further, they do not rely on a resurgence of interest in methods of building procurement which seek to integrate design and construction.

7.6.2 Strategic plan for building designers

Figure 7.13 shows the strategic plan for successful application of rules and evaluation metrics by building designers.

Figure 7.13: Strategic plan for the successful application of DFM principles by building design organisations

1	Strategic goal	*To design for building production as effectively as for building form and function*
2	Application focus	*C0: Building Product level, C1: Building Assembly level and C2: Building Sub-assembly level.*
	Application opportunities	*Building design: all stages. Bespoke component design: concept stage and scheme stage.*
	Application methods	*Basic or Advanced manual methods. Possibly computerised data validation routines and libraries of features.*
3	Relevant rules	*New standard production design improvement rules.*
	Sources of rules	*Generate internally.*
	Relevant metrics	*Expert knowledge metrics.*
	Sources of metrics	*Generate internally.*
4	Success focus	*P0.0: building construction processes to P2.3: component assembly activities.*
	Success methods	*Primary: elimination of building components; and rationalisation of building components. Secondary: rationalisation of design data; automation of design information; component design to: simplify construction; simplify installation; simplify assembly; consolidate parts; and for ease of manufacture.*

All industry practitioners felt that the strategic goal of designing for building production as effectively as for building form and function was a good starting point for building designers. However, construction managers and component producers suggested that the strategic goal should be set higher in the future because in their opinion not all building designers deal with form and function adequately.

With regard to application issues, there was agreement amongst building designers that their focus should be on component levels C0, C1 and C2, in that order. However, they were uncertain whether there was sufficient repetition of design certainty in their work for them to be able to develop data validation routines or libraries of features as application methods for rules and metrics. Further, they were certain that they could not develop generic component models. Accordingly, the diagram shown in Figure 7.10 above was revised by the author to indicate that generic component models are of low feasibility for building designers. Also, generic component models were removed from the list of possible application methods in the strategic plan shown in Figure 7.13.

Building designers recognised that existing DFM rules and metrics would be of little use to them, and that new rules and metrics were required. They saw that it would be technically feasible and economically viable for them to generate new rules and metrics with the assistance of construction managers and bespoke component producers. However, they were not confident that they would ever be able to make the time available to do this.

With regard to success issues, building designers felt that elimination and rationalisation of building components could be their primary methods of improving productivity and quality. Accordingly, Figures 7.11 and 7.13 were also revised by the author after the interviews.

7.6.3 Strategic plan for construction managers

Figure 7.14 shows the strategic plan for construction management organisations.

Figure 7.14: Strategic plan for the successful application of DFM principles by construction management organisations

1	Strategic goal	*To improve construction productivity and quality by influencing the design of buildings and bespoke building components.*
2	Application focus	*C1: Building Assembly level, and C2: Building Sub-assembly level.*
	Application opportunities	*Building design: scheme stage and detail stage.* *Bespoke component design: scheme stage and detail stage.*
	Application methods	*Basic or advanced manual methods.*
3	Relevant rules	*New standard production design improvement rules.*
	Sources of rules	*Generate internally.*
	Relevant metrics	*Expert knowledge metrics.*
	Sources of metrics	*Generate internally.*
4	Success opportunities	*P0.3: building construction task to P2.3 component assembly task.*
	Success methods	*Primary: component design to simplify assembly; component design to simplify construction; and component design to simplify installation.* *Secondary: elimination of building components; and rationalisation of building components.*

Overall, the strategic plan for construction managers was seen as being technically feasible and economically viable. There was common agreement amongst interviewees that the strategic goal for construction managers was realistic, because this type of organisation already has to try to improve productivity and quality by influencing design. However, construction managers felt that currently most of their efforts to improve productivity and quality were spent trying to reduce production problems brought about by "poor design".

One building designer felt that construction managers could best influence design by developing rules and metrics for use by architects and consulting engineers. However, this building designer felt it was unlikely that any construction management organisation would "hand-over" rules and metrics developed at their own expense without charging a fee. Another building designer suggested that construction management organisations would have to be provided with rules and metrics developed by building designers in conjunction with organisations which produce and install bespoke components. This designer suggested that production knowledge in the construction industry was concentrated amongst these types of organisations rather than amongst construction managers.

Once again the issue of finding time to carry out the strategic plan was seen as being a major problem. This was a recurring theme: all the interviewees felt that they and their colleagues have no spare time available. There was common agreement that this was because their organisations had gone from being "fat" with plenty of personnel to being "skeletal" with not enough personnel. They felt that applying rules and metrics could reduce their workload, but in the short-term they would have to increase their workload to develop the rules and metrics. However, the interviewees felt that personnel at all levels have to work so hard just to carry out their routine duties, that they simply cannot do any more work.

7.6.4 Strategic plan for designers / producers of standard components

Figure 7.15 shows the strategic plan for organisations which design and produce standard building components.

Figure 7.15: Strategic plan for the successful application of DFM principles by standard component producers

1	Strategic goal	*To design for ease of component manufacture, simplification of component assembly and installation, and improved building construction.*
2	Application focus	*C3: Part, formed material and/or formless material level.*
	Application opportunities	*Standard component design: concept stage, scheme stage and detail stage.*
	Application methods	*Bills of materials, generic product models, and/or generic component models.*
3	Relevant rules	*Existing DFM rules and modified DFM rules.*
	Sources of rules	*Existing DFM methodologies.*
	Relevant metrics	*Existing DFM metrics and new work measurement metrics.*
	Sources of metrics	*Existing DFM methodologies and internal work measurement.*
4	Success opportunities	*P2.3 component assembly activities to P3.3 component manufacture activities.*
	Success methods	*Primary:* *component design to simplify assembly; component design to consolidate parts; component design for ease of manufacture; rationalisation of design data; automation of design information; and automation of production information.* *Secondary:* *component design to simplify installation; and component design to simplify construction.*

As described in Chapter 2, standard components include bricks, chipboard, plasterboard, floor tiles, door hinges etc which are typically sold through builders merchants.

Interviewees recognised that successful application of rules and metrics could bring about better component prices and quality. However, they were more interested in standard components being designed to improve construction. Building designers felt that standard component designers / producers would need the assistance of other types of organisations to develop rules and metrics for building construction. Further, building designers, construction managers and bespoke component producers felt it was unrealistic to expect designers of standard components to take the initiative in developing rules and metrics for building construction because of lack of practical construction experience.

7.6.5 Strategic plan for producers / installers of bespoke components

Figure 7.16 shows the strategic plan for organisations which produce and install bespoke building components.

Figure 7.16: Strategic plan for the successful application of DFM principles by bespoke component producers

1	Strategic goal	*To improve the productivity and quality of component assembly, component installation and building construction by influencing the design of components*
2	Application focus	*C2: Building Sub-assembly level.*
	Application opportunities	*Building design: detail stage.* *Bespoke component design: scheme stage and detail stage.*
	Application methods	*Data validation routines and Advanced or Basic manual methods.* *Possibly libraries of features and generic component models.*
3	Relevant rules	*Depending on type of component, existing DFM rules, modified DFM rules, and new rules have varying levels of relevance.*
	Sources of rules	*Existing DFM methodologies and/or generate internally.*
	Relevant metrics	*New work measurement metrics and expert knowledge metrics.*
	Sources of metrics	*Generate internally.*
4	Success opportunities	*P1.3 component placing / installing activities to* *P2.3 component assembly activities.*
	Success methods	*Primary:* *component design to simplify installation,* *component design to simplify assembly.* *Secondary:* *component design to simplify building construction.*

This strategic plan was of most interest to interviewees. There was common agreement that this type of organisation is now responsible for most of the production carried out in the construction industry. It was also felt that organisations in this category varied widely in the sophistication of their production plant and process. Most interestingly, building designers and construction managers shared a common agreement that bespoke component producers with sophisticated production facilities seemed to have as many productivity and quality problems as those with rudimentary production facilities. Further, building designers and construction managers expressed disappointment that producers which had invested in very sophisticated plant seemed "incapable of putting it to good use". Several interviewees suggested that the development of rules and metrics which dealt with bespoke manufacture and assembly were urgently required by this type of organisation.

Although the strategic plan was considered to be both feasible and viable by the interviewees, there was particular concern as to the capability of this type of organisation to develop application methods. This concern was based on the perception that bespoke component producers "can't use the software they've already got". However, despite the concern of interviewees, the action research intervention reported in Chapter 5 demonstrates that an organisation which produces and installs bespoke components can develop and use a computerised application framework for rules and metrics.

7.6.6 Strategic plan for component installers

Figure 7.17 shows the strategic plan for labour only component installers.

Figure 7.17: Strategic plan for the successful application of DFM principles by component installers

1	Strategic goal	*To improve the productivity and quality of component installation by influencing the design of components.*
2	Application focus	*Possibly C3: Part, formed material and/or formless material level.*
	Application opportunities	*Possibly Building design: detail stage.* *Possibly Standard component design: detail stage.*
	Application methods	*Basic paper-based methods.*
3	Relevant rules	*New standard production design improvement rules.*
	Sources of rules	*Generate internally.*
	Relevant metrics	*New work measurement metrics.*
	Sources of metrics	*Generate internally.*
4	Success opportunities	*Possibly P0.2 Building construction tasks to P2.2 component assembly tasks.*
	Success methods	*Component design to simplify installation;* *Automation of production information.*

Interviewees regarded this type of organisation as having considerable knowledge to offer. Further, it was suggested that it was imperative for this knowledge to be captured as rules and metrics before the most experienced and capable installation operatives retired. One construction manager suggested that this type of organisation could not be expected to take the initiative in developing rules and metrics. Further, there was a common opinion that labour only component installers were averse to any form of documentation, or as one interviewee put it, "these people don't even want to fill in a time-sheet".

Generally, it was felt that the strategic plan was feasible and viable. However, several interviewees suggested that labour only component installers should be invited, and if necessary paid, to participate in the development of rules and metrics by other types of organisations.

7.6.7 Overall assessment of strategic plans

There was common agreement amongst the interviewees that the strategic plans and supporting figures had clarified how they could successfully apply DFM principles. Their previous concerns about "not knowing where to start" had been greatly reduced. In particular, it had become clear to them that rules and metrics are applied during design to improve the success of production. Also, they now understood that rules and metrics can be formulated to improve production in any environment, whether that be in a fully automated factory or outside on a construction site. This was a major step forward, as prior to the presentation of the strategic plans, the interviewees had viewed DFM as being synonymous with design standardisation and factory production.

With regard to the future implementation, there was common agreement amongst all seven interviewees that the all five strategic plans were technically feasible and economically viable. However, there was also a concensus amongst the interviewees that it would be very difficult for them to find the time to formulate rules and metrics. This suggests that many inventions similar to that described in Chapter 5 will be required to achieve widespread successful application of DFM principles.

7.7 Chapter Conclusion

In this chapter, strategies for achieving successful application of DFM principles throughout the construction industry have been presented. Firstly, issues concerning the development of rules and metrics were explored. These have been categorised as: classification issues; formulation issues; application issues; and success issues. Then, individual strategic plans for specific types of construction organisations have been proposed and explained. Attitudes of industry practitioners towards these strategic plans have been reported. The principal findings of this part of the research are stated below.

The research findings reported in earlier chapters suggest that the successful application of DFM principles in the construction industry is technically feasible and economically viable. However, the research findings also suggest that further development of DFM principles is required to facilitate their general application and widespread success. Consideration of the factors which different construction organisations would have to address in the development of DFM principles resulted in the identification of four major issues. These were categorised as: classification issues; formulation issues; application issues; and success issues.

A classification system for rules and metrics was developed. This included the development of a nomenclature for building component levels and building production phases. The system was regarded as being easy to understand and fit for purpose by industry practitioners.

Further, construction organisations have been classified as follows: building designers; construction managers; designers and producers of standard building components; producers and installers of bespoke building components; and labour only component installers. These classifications were agreed to be comprehensive and valid by industry practitioners.

Issues concerning the formulation of rules and metrics have been explored. The relevance of six types of rules and metrics to each of the five different types of construction organisations has been evaluated.

Analysis of issues concerning the application of rules and metrics revealed that different methods are appropriate for different construction organisations. The relevance of seven application methods to each of the different types of construction organisations has been evaluated.

Similarly, analysis of issues concerning the potential success of rules and metrics revealed that different opportunities are feasible and viable for different organisations. The relevance of ten productivity and quality improvement methods to each of the different types of construction organisations has been evaluated.

Individual strategic plans have been developed for specific types of construction organisations. Each plan defines appropriate actions to address formulation issues, application issues and success issues. The strategic plans were judged to be both feasible and viable by industry practitioners.

8.0 Discussion

8.1 Introduction

In this chapter, the research focus is revisited and the major themes of the research are discussed. Also, the impact of the research on industry is described.

8.2 Research Focus

As described in the Preface, the research reported in this thesis began with an exploratory literature review and unstructured interviews focused on: *the use of design to improve construction industry productivity and quality.*

From this very broad focus, the research became increasingly specific. Further exploratory investigations led to the definition of two research questions which dealt specifically with DFM. Then, inductive research, comprising further literature review and field survey, resulted in the generation of the hypothesis: *DFM principles can be applied successfully to building components and buildings*

The deductive research which followed comprised field work in two organisations. Findings from the field work suggested that the research hypothesis was valid. Thereafter, the research broadened out once more. Strategic plans which, through DFM principles, facilitate *the use of design to improve construction industry productivity and quality* were developed and validated.

It is not the purpose of this thesis to suggest that DFM alone can solve all the productivity and quality problems of the construction industry. However, the following discussion indicates that DFM principles can play a significant part in improving productivity and quality in the construction industry.

8.3 Research Themes

8.3.1 Construction design and manufacturing design are often different

Review of literature revealed that low construction productivity and poor construction quality are widely reported. Findings also indicate that the need to improve productivity and quality has been recognised by the construction industry, and by its public and private sector clients, since the early 1960's. Review of literature also revealed that DFM methodologies have been very successful in improving productivity and quality in the manufacturing industry since the 1970's. Literature review provided little evidence of existing DFM methodologies being applied to building components, and no evidence of them being applied to entire buildings. Further, no reports were found of alternative formal production design methodologies being used in the construction industry.

Analysis of construction design and manufacturing design indicates that they are often different. This is because design in the construction industry is customer-led and location-specific far more often than it is in the manufacturing industry. Analysis identified that when building design, and building component design, are customer-led and location-specific the types of design information generated tend to be different to those prevalent in the design of standard and custom manufactured goods. For example, Bills of Materials are not generated during the design of buildings. Analysis also identified that building design, and building component design, are seldom producer-led and market-specific. It was explained that as a result the types of design activities carried out tend to have less potential for improving productivity and quality than those common in the design of standard and custom manufactured goods. For example, the development of mass produced building-specific discrete assemblies is seldom possible during building design because this requires a high repetition of pre-order design certainty.

8.3.2 Existing DFM methodologies are not widely applicable to buildings

In Chapter 4, the findings of inductive research comprising literature review and field survey were reported and discussed. An overview of existing DFM methodologies was provided, and an analysis of issues affecting the application and the success of these methodologies was presented.

Analysis revealed that the design information and design activities which have enabled the successful application of existing DFM methodologies to standard and custom manufactured goods are seldom found in the design and production of bespoke and hybrid buildings. As a consequence, opportunities for successfully applying existing DFM methodologies are mainly limited to standard and custom buildings.

Analysis also revealed that existing methodologies can be applied to discrete engineered standard and custom building components, such as shower water heater units. However, whilst this may improve the productivity and quality of component assembly, this will not necessarily improve the productivity and quality of overall building construction. This is because, whilst it may result in the installation of the shower heater unit being simpler, the installation of adjacent components supplied by others could become more complicated.

8.3.3 There are opportunities for successful application of DFM principles

Having identified the limitations of existing DFM methodologies, the analysis contained within Chapter 4 addressed the potential for successful application of standard production design improvement rules and standard production design evaluation metrics.

It is evident that standard production design improvement rules (**rules**) and standard production design evaluation metrics (**metrics**) are the two fundamental principles of DFM. It was determined that existing DFM rules are relevant to some aspects of building component production and building construction. Analysis of literature review findings revealed that existing DFM metrics are relevant to the production of standard discrete engineered building components. However, further analysis revealed that they are not relevant to the production of other types of building components and to the construction of whole buildings.

8.3.4 DFM principles can be applied successfully to building components

Chapter 5 described an action research intervention designed to determine whether or not rules and metrics can be applied successfully to building components. During the intervention, it was identified that many existing DFM rules and DFM metrics focus on processes and plant improvements which are not relevant to the production of bespoke building components.

Most significantly, the intervention demonstrated that the application of rules and metrics can be successful in improving the productivity and quality of building component production. Further, the action research intervention demonstrated that application of rules and metrics is both technically feasible and economically viable for the many small-, and medium-sized (SME) businesses which manufacture building components. Furthermore, the intervention demonstrated that application of rules and metrics to building components can lead to significant financial and organisational business benefits for their producers.

8.3.5 DFM principles can be applied successfully to buildings

In Chapter 6, a case study designed to determine whether or not rules and metrics can be successfully applied to buildings was described. It was demonstrated, using the case of assisted bathrooms for a healthcare facility, that new rules, modified DFM rules, and existing DFM rules can be successfully applied to buildings. It was also demonstrated that an approach using subjective expert knowledge based metrics can be used to evaluate alternative building designs. These are a more economically viable alternative to metrics based on work measurement. It was explained that for such metrics to be valid they must comprise an appropriate balance of all necessary expert knowledge.

It was identified that the development of BoMs, or an equivalent, for buildings would assist the application of DFM principles to whole buildings. This is because BoMs help designers see the affects of eliminating or modifying one component on all other parts, sub-assemblies and assemblies. It was explained that rules and metrics need to be applicable irrespective of client type or mode of procurement. It was suggested that to make this possible they will need to be supported by comprehensive and detailed instructions.

Most significantly, the case study demonstrated that the application of rules and metrics can be successful in improving the productivity and quality of building construction. Further, the case study demonstrated that it is both technically feasible and economically feasible to apply rules and metrics on individual one-off construction projects. Furthermore, case study findings suggest that application of rules and metrics could lead to financial and organisational business benefits for construction project participants. In this case, a range of participants were involved from a multi-national, Contractor-X, to SMEs, such as a floor laying contractor.

8.3.6 DFM principles can be applied throughout the construction industry

In Chapter 7, issues concerning the development of rules and metrics were explored. Then, individual strategic plans for specific types of construction organisations were proposed. Attitudes of industry practitioners towards these strategic plans were reported.

Three types of rules were defined: existing DFM rules, modified DFM rules and new rules. Three types of metrics were defined: existing DFM metrics, new work measurement metrics and expert knowledge metrics. At least one type of rule and one type of metric are relevant to each type of construction organisation. Seven types of application methods for rules and metrics were defined: basic manual methods, advanced manual methods, data validation routines, libraries of features, generic component models, generic product models and bills of materials. At least one of these application methods is relevant to each type of construction organisation. Ten productivity and quality improvement methods were defined.

These range from building design to eliminate components, to rationalisation of design data. At least one of these improvement methods is relevant to each type of construction organisation.

Individual strategic plans were developed for specific types of construction organisations. Each plan defines appropriate actions to facilitate: the formulation of rules and metrics; the application of rules and metrics; and the success of rules and metrics. The strategic plans were judged to be both technically feasible and economically viable by industry practitioners.

8.4 Impact of the Research Experience

The research process, and the subsequent generation of strategic plans for successful application of DFM principles, has had an impact at the following levels: Contractor-X, Supplier-Y, the construction industry and the researcher. The impact on each of these levels is now discussed.

8.4.1 Impact on Contractor-X

As a result of the case study reported in Chapter 6, Contractor-X has improved construction productivity and quality for a major healthcare facility. Further, Contractor-X now has improved understanding of component manufacturers and component assemblers cost drivers and operational problems. Furthermore, at a meeting held several months after the field trial there was unanimous agreement that more applications of rules and metrics should be carried out. These future applications will have further positive impact on Contractor-X.

8.4.2 Impact on Supplier-Y

As a result of the action research intervention reported in Chapter 5, Supplier-Y has a formal production design method. As a consequence, there are now better working relationships between estimating and production departments in particular, and between office personnel and production operatives in general. Most significantly, Supplier-Y's non-productive costs have fallen by forty-seven percent whilst its financial turnover has increased by twenty percent.

8.4.3 Impact on the construction industry

The exploratory research reported in Chapter 2, provides an in depth analysis of how design affects production options. As explained in Appendix L, this analysis has been disseminated to the construction industry through the professional publications, *the architects' journal* and *Manufacturing Engineer*.

The inductive research reported in Chapter 4, provides an analysis of the relevance of standard production design improvement rules and standard production design evaluation metrics. This analysis has also been disseminated to the construction industry through *the architects' journal* and *Manufacturing Engineer*.

The deductive research reported in Chapter 5, provides building component producers with practical guidance about how to successfully apply rules and metrics within their businesses. This information has been disseminated through *Manufacturing Engineer*. The deductive research reported in Chapter 6, provides construction managers with practical guidance about how to successfully apply rules and metrics to buildings. This information will be disseminated through an appropriate academic journal. The strategic plans presented in Chapter 7, provide guidance about rules and metrics for a comprehensive range of construction organisations. Each strategic plan addresses formulation issues, application issues and success issues. This information will be disseminated through the academic journal, *Construction Management and Economics*.

8.4.4 Impact on the researcher

The research experience has enabled the author to develop skills in the areas listed below.

- Selection of research strategies and development of research instruments.
- Preparation of research proposals which are attractive to industry.
- Presentation of innovative ideas, methods and interpretations to a wide range of people in different types of organisations.
- Planning, organisation and control of research work in industry.
- Managing change in industry.
- Analysis and presentation of research findings.
- Technical writing in different styles to suit the editorial requirements of different types of publications.

8.5 Chapter Conclusion

In this chapter, the research focus has been revisited, the major themes of the research have been discussed, and the impact of the research has been described.

9.0 Conclusions

9.1 Introduction

In this final chapter, the research conclusions are stated, the originality and contribution to knowledge of the research are described, and recommendations for further research are provided.

9.2 Research Conclusions

- There are limited opportunities to successfully apply existing DFM methodologies in their current form to buildings and building components.
- Many existing DFM <u>rules</u> can be successfully applied to buildings and building components.
- Few existing DFM <u>metrics</u> can be successfully applied to buildings and building components.
- It is feasible and viable to develop new standard production design improvement rules specifically for buildings and building components.
- It is feasible, but not always viable, to develop standard production design evaluation metrics for buildings and building components using work measurement techniques.
- It is feasible and viable to develop new standard production design evaluation metrics specifically for buildings and building components based on subjective expert knowledge.
- The development of BoMs, or an equivalent, for buildings would assist the application of rules and metrics to whole buildings.

- The research demonstrated that application of rules and metrics in the construction industry is technically feasible and economically viable.
- The research showed that application of rules and metrics can lead to significant financial and organisational business benefits.
- Strategic plans for the successful application of rules and metrics throughout the construction industry have been judged to be both technically feasible and economically viable by industry practitioners.
- Most significantly, the research demonstrated that rules and metrics can be applied successfully to buildings and building components.

9.3 Originality

9.3.1 Definitions of originality

Phillips and Pugh (1994) list fifteen alternative ways in which doctoral scholars may be considered to have demonstrated originality. Their list is shown below.

- Setting down a major piece of new information in writing for the first time.
- Continuing a previously original piece of work.
- Carrying out original work designed by the supervisor.
- Providing a single original technique, observation, or result in an otherwise unoriginal but competent piece of research.
- Having many original ideas, methods and interpretations all performed by others under the direction of the postgraduate.
- Showing originality in testing somebody else's idea.
- Carrying out empirical work that hasn't been done before.

- Making a synthesis that hasn't been made before.
- Using already known material but with a new interpretation.
- Trying out something in this country that has previously only been done in other countries.
- Taking a particular technique and applying it in a new area.
- Bringing new evidence to bear on an old issue.
- Being cross-disciplinary and using different methodologies.
- Looking at areas that people in the discipline haven't looked at before.
- Adding to knowledge in a way that hasn't previously been done before.

As described below, the research reported in this thesis is original in three of the ways listed by Phillips and Pugh.

9.3.2 Using already known material but with a new interpretation

The literature reviews reported in Chapter 2 and Chapter 4 revealed considerable published material dealing with existing DFM methodologies. The research has shown originality in the interpretation and application of this published material. In particular, standard production design improvement rules and standard production design evaluation metrics have been defined as the fundamental principles of all existing DFM methodologies irrespective of their format, content and use.

Further, standard rules and metrics have been interpreted as being applicable to bespoke design in the construction industry. Furthermore, standard rules and metrics have been interpreted as having the potential to improve bespoke production in factories and bespoke construction on sites. In this research, existing DFM methodologies have been interpreted as valuable examples to be understood rather than universal ideals which can be copied exactly in all industries.

9.3.3 Carrying out empirical work that hasn't been done before

The action research intervention reported in Chapter 5 was original in the way in which rules and metrics were applied during design, and in the way in which productivity and quality improvements were subsequently achieved during production. With regard to the application of rules and metrics, originality was required because Supplier-Y does not carry out concept or scheme design work. Its input is restricted to the detail design stage. Further, Supplier-Y's does not receive direction about how to design components for overall building construction from first level suppliers. These factors mean that Supplier-Y can not apply DFM in the same way as marketing / assembly businesses such as the Ford Motor Company. Neither, can it apply DFM in the same way as component manufacturers working in fixed supply chains with companies such as Ford. With regard to the success of rules and metrics, originality was required because Supplier-Y produces and installs bespoke building components. As a consequence, many of the productivity and quality improvement strategies, such as parts consolidation, which have often resulted from the application of DFM are not relevant to Supplier-Y.

Similarly, the case study reported in Chapter 6 was original in the way in which rules and metrics were applied during design, and in the way in which productivity and quality improvements were subsequently achieved during production. In particular, an original type of standard production design evaluation metric based on expert knowledge was successfully trialed. Also, standard production design improvement rules from the manufacturing industry were applied to buildings.

9.3.4 Having original ideas, methods and interpretations performed by others

Having many original ideas, methods and interpretations all performed by others under the direction of the postgraduate is a way of demonstrating originality which is particularly relevant to action research. In the intervention reported in Chapter 5, the author guided the introduction of rules and metrics in Supplier-Y. Throughout the intervention, there was a person in the business working full-time, under the direction of the author, performing actions, such as cataloguing component characteristics and writing software programs. Further, personnel at all levels of the business from the managing director to general operatives were involved in performing the author's ideas, methods and interpretations under his direction.

Similarly, during the case study reported in Chapter 6, attendees at the design co-ordination meeting for assisted bathrooms performed design improvements and design evaluations using methods and interpretations devised by the author under his direction. In contrast to the action research intervention where people work for one organisation, in the case study people from several different organisations performed the author's methods and interpretations. Some of these people were employed by Contractor-X but the majority were independent building designers, building component manufacturers, and building component installers.

9.4 Contribution To Knowledge

The literature review reported in Chapter 2 revealed that the proportion of construction productivity and quality problems attributable to design has remained at about fifty percentage for the past twenty years (BRE, 1981; Barber *et al*, 2000). Literature review also revealed that, although there has been some recognition of DFM's potential to improve construction productivity and quality in recent years, the following two question had yet to be answered:

- how DFM can be *applied* during building component design and building design?, and
- how can DFM application be *successful* in improving the productivity and quality of building component production and building construction?

The research which was subsequently carried out to answer these questions resulted in the contribution to knowledge described below.

Individual strategic plans for the successful application of DFM principles have been provided for five specific types of construction organisations. These five organisations cover the full range of work carried out in the construction industry. These strategic plans have been judged to be both technically feasible and economically viable by industry practitioners. Each strategic plan addresses formulation, application and success issues.

The strategic plans are given credibility by the field research having been carried out in "live" settings. Especially, as the field research has focused on the most challenging applications for DFM in the construction industry: bespoke building components and bespoke buildings.

The field research demonstrates that it is possible for DFM principles to be applied successfully in the construction industry by both Small to Medium sized Enterprises and multi-national businesses. Further, the detailed descriptions of field work contained in Chapter 5 and Chapter 6 offer practical guidance for industry practitioners working in these different types of businesses.

The research makes a contribution in the area of research methodology. It has shown that threats to research validity in the construction industry can be counteracted by applying a quasi-experimental perspective to action research interventions and case studies. Further, it has been demonstrated that research carried out on a self-funded part-time basis by a single construction industry practitioner can yield notable information.

9.5 Recommendations for Further Research

In this thesis, DFM principles have been defined as standard production design improvement rules and standard production design evaluation metrics. Research recommendations concerning the application of rules and metrics to improve productivity and quality in the construction industry are provided below.

Although ten examples of productivity and quality improvement methods which could result from the application of rules and metrics were provided in Chapter 7, a comprehensive analysis, cataloguing and classification of improvement methods is required to inform the formulation of rules and metrics. Literature reviews and field surveys are needed to gather the required information.

Rules have been classified into the following three categories: existing DFM rules, modified DFM rules and new rules. Metrics have been classified into the following three categories: existing DFM metrics, new work measurement metrics and expert knowledge metrics. Industry examples of the formulation, application and testing of these different categories of rules and metrics would provide valuable practical guidance for construction organisations. Action research methodologies are needed to generate this type of in-depth guidance.

Application methods for rules and metrics have been classified into the following seven categories: basic manual methods, advanced manual methods, data validation routines, libraries of features, generic component models, generic product models and bills of materials. The development and testing of these application methods in industry could provide further detailed guidance for construction organisations. Again, action research methodologies would be appropriate for these investigations.

The development of Bills of Materials, or an equivalent, for buildings would assist the application of rules and metrics to whole buildings. This is because Bills of Materials help designers see the affects of eliminating or modifying one component on all other parts, sub-assemblies and assemblies. Development and testing would require numerous case studies involving several different organisations.

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Application
of
Design for Manufacture Principles
to
Building Design and Construction

Stephen John Fox

A thesis submitted in partial fulfilment of the requirements of
Sheffield Hallam University
for the degree of Doctor of Philosophy

Appendices

March 2001

A.0 EXPLORATORY INTERVIEWS

A.1 Introduction

In this appendix, details about the exploratory interviews reported in Chapter 2 are provided, and their contribution to the author's research training is described. The purpose of the interviews was to explore issues that emerged during initial literature review.

As reported in Chapter 2, the review focused on the use of design to improve construction industry productivity and quality. This led to the emergence of two themes which construction industry practitioners could offer informed opinions about: continued low productivity and poor quality in the construction industry; and lack of DFM application in the construction industry. These issues were the subject of unstructured interviews with five industry practitioners.

A.2 Interview Design

The interviewees are professional contacts of the author, selected by him because of their high level of training and experience. One is an architect employed as the design director of a national building contractor, one is a consulting engineer employed as a director of a multi-disciplinary design practice, one is an interior designer with his own practice, one is a construction manager with a multi-national contractor and one is a commercial director with another multi-national contractor. The interviews were conducted individually at the interviewees' offices outside working hours.

An unstructured format was chosen for the interviews because of their exploratory nature. The author had two themes to discuss rather than predetermined questions which could be recorded on a fully structured schedule.

It was considered acceptable to use a convenience sample because at this stage the research was concerned with gaining an overall appreciation of the issues involved, rather than carrying out a detailed analysis. However, the interviewees did not participate in subsequent stages of the research because their existing relationships with the author could have resulted in them demonstrating positive bias.

A.3 Research Training

The exploratory interviews provided the author with the opportunity to learn about, and select from, alternative interview techniques. Carrying out unstructured interviews with five established professional contacts provided the author with a gentle introduction into field survey work.

B.0 FIRST SET OF STRUCTURED INTERVIEWS

B.1 Introduction

The field survey reported in Chapter 4 comprised two sets of structured interviews and one postal questionnaire supported by follow-up interviews. This appendix provides information about the first set of structured interviews. A sample of the interview schedule is presented, and its design is discussed. Also, the contribution of the first set of structured interviews to the author's research training is described.

B.2 Sample Interview Schedule

Literature survey had identified that existing DFM methodologies enable users to integrate production best practice into their designs and to select the best available combinations of materials, parts and processes. The purpose of the first set of structured interviews was to determine how, if at all, these activities are carried out in the construction industry.

These interviews were the first field work carried out with Contractor-X. In order to ensure their continued involvement in the research, it was necessary to demonstrate competence. Accordingly, it was important that the author's inexperience as a researcher did not result in interviews which were poorly conducted and/or overran their agreed duration of thirty minutes. Therefore, the interview schedule was designed to be straightforward and short.

Fifteen industry practitioners were sampled. All the interviewees were directly employed by Contractor-X or worked with Contractor-X during building design and/or building production. All fifteen of them had experience of working on buildings with values of up to £50 million. The author carried out the interviews at three offices located in the London area over a period of two days.

Five of the fifteen industry practitioners were interviewed during the first day. Of these, three were senior architects employed by a multi-national architectural practice to oversee the design of buildings. Two of the interviewees were consulting engineers employed by a multi-disciplinary firm to carry out the engineering design of buildings. These five participants were introduced to author by Contractor-X. They were interviewed at two offices in central London.

The remaining ten industry practitioners were interviewed on a second day. Of these, five interviewees were directly employed by Contractor-X. One was a project manager, another interviewee was a design co-ordinator. The three other interviewees who were employed by Contractor-X were a construction manager, a Mechanical & Engineering (M&E) services manager, and a commercial manager.

In addition, five interviewees were employed as senior managers by companies which design, manufacture, supply and/or place or install components. Each company specialises in one of the following building elements: substructure, superstructure, M & E, walls and ceilings, floors. All of these ten participants were interviewed by the author at Contractor-X's Head Office.

OPENING STATEMENT

Thank you for taking the time to participate in this interview. During the interview, I will ask you some questions about design in the construction industry.

Trials of this interview have been carried out to make sure that it can be completed in half an hour. Your interview answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

Please note that all interviewees are asked the same questions in the same way, and there are no "right" or "wrong" answers to any of the questions. After the interview there will be a few minutes for clarification of any issues which are of particular interest to you.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q1	*PLEASE DESCRIBE HOW YOU INTEGRATE CONSTRUCTION BEST PRACTICE INTO BUILDING DESIGNS*

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PROBE	*HOW WOULD YOU DEFINE CONSTRUCTION BEST PRACTICE?*

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PROBE	*CAN YOU GIVE ME SOME RECENT EXAMPLES OF WHERE YOU HAVE INTEGRATED BEST PRACTICE INTO DESIGNS?*

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INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q2	*PLEASE DESCRIBE HOW YOU SELECT THE BEST AVAILABLE COMBINATIONS OF COMPONENTS AND PROCESSES*

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PROBE	*CAN YOU GIVE ME SOME RECENT EXAMPLES OF WHERE YOU HAVE SELECTED THE BEST AVAILABLE COMBINATIONS OF COMPONENTS AND PROCESSES?*

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PROBE	*HOW CONFIDENT ARE YOU THAT YOU ALWAYS SELECT THE BEST AVAILABLE CONSTRUCTION COMPONENTS AND PROCESSES?*

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INTERVIEW SCHEDULE			PAGE .... OF .....
SUPPLEMENTARY PAGE			
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

CLOSING STATEMENT

Thank you for taking the time to participate in this interview. Having carefully studied your comments, it may be necessary for me to telephone you for a few minutes to clarify minor details.

As stated at the beginning of the interview, your answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

B.3 Schedule Design

At the time of the interviews, the author had very little practical experience of field survey work. Therefore, the schedule was designed to make the interviewing processes as straightforward as possible. To achieve this, the number of questions to be asked was limited to two. This eliminated the need for question routing on the schedule. Also, questions which did not require the use of prompt cards were asked. However, the author recognised that having only two questions to ask, the opportunity to elicit full answers should not be missed. Therefore, probes were included in the schedules. When designing the questions, the author sought to adhere to Hoinville and Jowell's (1977) guidelines. These are to avoid: long questions; multiple barrelled questions; questions involving jargon; leading questions; and biased questions.

B.4 Research Training

The first set of structured interviews provided the author with the opportunity to design questions and structure them within a simple schedule. Using the schedule with fifteen industry practitioners provided the author with experience in the interviewing process. This experience highlighted to the author that adhering to good interview technique is not always easy. For example, "listening more than speaking", and "looking like it is a pleasure to carry out the interview" can be challenging after seven hours of asking the same questions and hearing quite similar responses.

C.0 SECOND SET OF STRUCTURED INTERVIEWS

C.1 Introduction

The field survey reported in Chapter 4 comprised two sets of structured interviews and one postal questionnaire supported by follow-up interviews. This appendix provides details about the second set of structured interviews. A sample of the interview schedule is provided, and its design is discussed. Also, the contribution of these structured interviews to the author's research training is described.

C.2 Sample Interview Schedule

Literature survey had identified that existing DFM methodologies provide their users with a means of rapidly evaluating the relative production times and production costs for alternative designs. The purpose of the second set of interviews was to determine how, if at all, production times and costs for alternative designs are evaluated in the construction industry.

The interviews were carried out with a purposive sample of fifteen industry practitioners. These were different people to those who had participated in the first set of structured interviews. However, the same mix of occupations was sampled and, again, all the interviewees were directly employed by Contractor-X or worked with Contractor-X during construction projects. The interviews were conducted by the author during one day at a Contractor-X site office in East London. All of the interviewees were involved in the design or construction of the building where the site office was located. None of them had been interviewed previously.

Again, three of the interviewees were architects employed by a multi-national architectural practice, however, on this occasion they were less senior and were involved in the day to day design of construction details. Similarly, two consulting engineers were interviewed who were also involved in the routine design work carried out during the construction of a large building.

Five of the interviewees were directly employed by Contractor-X. They were all involved in the construction of the building where the site office was located. One was the project manager, another was the design co-ordinator. Design co-ordinators are employed to control the issue of design information generated by architects, engineers, building component manufacturers and building component assemblers. The commercial manager was also interviewed, as was one of the site's construction managers, and one of the site's Mechanical & Engineering (M&E) services managers. In addition, five interviewees were employed as site managers by companies which design, manufacture, supply and/or place or install components. Each company specialises in one of the following building elements: substructure, superstructure, M & E, walls and ceilings, floors. Four of these interviewees were based on the site at the time, whilst the substructure contractor's site manager was asked to come back to site for an hour.

As reported in Appendix B, the first interview schedule designed by the author had been quite short and simple. This second interview schedule was more complex, with an increased number of questions and a structure which required prompt cards.

OPENING STATEMENT

Thank you for taking the time to participate in this interview. During the interview, I will ask you some questions about design in the construction industry.

Trials of this interview have been carried out to make sure that it can be completed in half an hour. Your interview answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

Please note that all interviewees are asked the same questions in the same way, and there are no "right" or "wrong" answers to any of the questions. After the interview there will be a few minutes for clarification of any issues which are of particular interest to you.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q1	*PLEASE DESCRIBE, WITH RECENT EXAMPLES, HOW YOU OBTAIN INFORMATION ABOUT POTENTIAL PRODUCTION **TIMES** FOR ALTERNATIVE DESIGN OPTIONS*

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PROBE	*WHAT IS YOUR OPINION ABOUT THE PRODUCTION TIME INFORMATION WHICH YOU OBTAIN?*

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SHOW THE INTERVIEWEE PROMPT CARD ONE

INTERVIEW SCHEDULE				PAGE .... OF .....
INTERVIEWEE		JOB TITLE		
ORGANISATION		DATE		

Q2	*HOW LONG DOES IT USUALLY TAKE YOU TO OBTAIN INFORMATION ABOUT POTENTIAL PRODUCTION **TIMES**?*

CATEGORY OF PRODUCTION **TIME** INFORMATION			up to 59 minutes	1 to 8 hours	1 day or more
OFF-SITE TIME REQUIRED to:	1	producing raw materials			
	2	processing formless materials			
	3	processing formed materials			
	4	manufacturing parts			
	5	prefabricating sub-assemblies			
	6	prefabricating assemblies			
ON-SITE TIME REQUIRED to:	7	placing formless materials			
	8	placing formed materials			
	9	installing parts			
	10	installing sub-assemblies			
	11	installing assemblies			
	12	forming interfaces			
			up to 59 minutes	1 to 8 hours	1 day or more

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q3	*PLEASE DESCRIBE, WITH RECENT EXAMPLES, HOW YOU OBTAIN INFORMATION ABOUT POTENTIAL PRODUCTION **COSTS** FOR ALTERNATIVE DESIGN OPTIONS*

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PROBE	*WHAT IS YOUR OPINION ABOUT THE PRODUCTION COST INFORMATION WHICH YOU OBTAIN?*

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SHOW THE INTERVIEWEE PROMPT CARD TWO

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q4	*HOW LONG DOES IT USUALLY TAKE YOU TO OBTAIN INFORMATION ABOUT POTENTIAL PRODUCTION **COSTS**?*				
CATEGORY OF PRODUCTION **COST** INFORMATION			up to 59 minutes	1 to 8 hours	1 day or more
OFF-SITE FINANCIAL **COSTS** INCURRED by:	13	producing raw materials			
	14	processing formless materials			
	15	processing formed materials			
	16	manufacturing parts			
	17	prefabricating sub-assemblies			
	18	prefabricating assemblies			
ON-SITE FINANCIAL **COSTS** INCURRED by:	19	placing formless materials			
	20	placing formed materials			
	21	installing parts			
	22	installing sub-assemblies			
	23	installing assemblies			
	24	forming interfaces			
			up to 59 minutes	1 to 8 hours	1 day or more

CLOSING STATEMENT

Thank you for taking the time to participate in this interview. Having carefully studied your comments, it may be necessary for me to telephone you for a few minutes to clarify minor details.

As stated at the beginning of the interview, your answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

PROMPT CARD ONE

CATEGORY OF PRODUCTION TIME INFORMATION			up to 59 minutes	1 to 8 hours	1 day or more
OFF-SITE TIME REQUIRED to:	1	producing raw materials			
	2	processing formless materials			
	3	processing formed materials			
	4	manufacturing parts			
	5	prefabricating sub-assemblies			
	6	prefabricating assemblies			
ON-SITE TIME REQUIRED to:	7	placing formless materials			
	8	placing formed materials			
	9	installing parts			
	10	installing sub-assemblies			
	11	installing assemblies			
	12	forming interfaces			

Terminology			
An example of	*raw materials*	is	*quarried rock*
An example of	*formless materials*	is	*screed*
An example of	*formed materials*	is	*vinyl flooring sheet*
An example of	*parts*	is	*waste trap*
An example of	*sub-assemblies*	is	*shower cubicle*
An example of	*assemblies*	is	*bathroom module*
An example of	*interfaces*	is	*joint between module and fabric*

PROMPT CARD TWO

CATEGORY OF PRODUCTION **COST** INFORMATION			up to 59 minutes	1 to 8 hours	1 day or more
OFF-SITE FINANCIAL **COSTS** INCURRED by:	13	producing raw materials			
	14	processing formless materials			
	15	processing formed materials			
	16	manufacturing parts			
	17	prefabricating sub-assemblies			
	18	prefabricating assemblies			
ON-SITE FINANCIAL **COSTS** INCURRED by:	19	placing formless materials			
	20	placing formed materials			
	21	installing parts			
	22	installing sub-assemblies			
	23	installing assemblies			
	24	forming interfaces			

Terminology			
An example of	*raw materials*	is	*quarried rock*
An example of	*formless materials*	is	*screed*
An example of	*formed materials*	is	*vinyl flooring sheet*
An example of	*parts*	is	*waste trap*
An example of	*sub-assemblies*	is	*shower cubicle*
An example of	*assemblies*	is	*bathroom module*
An example of	*interfaces*	is	*joint between module and fabric*

C.3 Schedule Design

At the time of the schedule design, the author had gained some experience of field survey work, and as a consequence, felt able to conduct more demanding interviews. However, a structured interview format was still used. This approach was selected in preference to semi-structured or unstructured formats because of the nature of the questions which needed to be answered. The questions had been defined by the literature survey findings and were of a quite detailed nature. Further, fifteen interviews had to be completed in one working day. Adhering to such a tight programme relied on none of the interviews over running. When piloting the schedule, it became clear that it would not always be possible to complete the interview in thirty minutes without the use of prompt cards.

C.4 Research Training

The second set of structured interviews provided the author with the opportunity to design questions and structure them within a more complex schedule incorporating prompt cards. Using this schedule with fifteen industry practitioners provided the author with more advanced experience of the interviewing process. These interviews were particularly challenging because they were carried out in one of Contractor-X's construction site offices where several of the participants were having to deal with pressing operational tasks. To ensure all the participants attended, a programme was agreed one week in advance with Contractor-X's senior personnel. One copy of this programme was issued to each interviewee with a formal memo reminding them when their attendance was required.

D.0 FIELD SURVEY QUESTIONNAIRE

D.1 Introduction

The field survey reported in Chapter 4 comprised two sets of interviews and one postal questionnaire supported by follow-up interviews. This appendix provides information about the questionnaire. A sample of the questionnaire is presented, the design of the questionnaire is discussed, and the methods used to analyse responses are explained. Also, the contribution of the questionnaire to the author's research training is described. Details of follow-up interviews are provided in Appendix E.

D.2 Sample Questionnaire

Literature survey findings suggest that the success of existing DFM methodologies rely on the concurrent design within and between businesses. The purpose of the questionnaire was to determine evidence of similar design activities in the UK construction industry.

As reported in Chapter 3, the questionnaire was posted to a purposive sample of two hundred and sixty-seven practitioners. Respondents were categorised as consultants, building component manufacturers (i.e. companies which design, manufacture and supply only components), and building component assemblers (i.e. companies which place and/or install components at site). A total of 127 (48%) responses were received. The questionnaire was posted with a covering letter which was printed on Contractor-X's stationery.

Dear

Re: Egan Report questionnaire

This questionnaire is part of our response to the Egan Report. Providing us with the most accurate answers possible will help us to develop more effective working relationships for all organisations involved in the construction process.

Your questionnaire answers will remain confidential and only summary results will be published, without any reference to specific organisations or individuals. Testing of the questionnaire has been carried out to make sure that it is easy to fill in and can be completed in about **twenty minutes**.

We request that you mail the completed questionnaire to us, in the enclosed self-addressed envelope. Please note that there are no "right" or "wrong" answers to the questions asked.

Thank you for taking the time to complete the questionnaire.

Yours sincerely,

1.	**IDENTIFICATION INFORMATION**
	Please write, in block capitals, the details asked for below in the spaces provided

1.1	What is the name of your organisation?	....

1.2	Please write one ✓ to the right of the *activity which makes the largest contribution to your organisation's financial turnover*	
	Consultancy e.g. architectural design / engineering design / construction management / quantity surveying etc.	
	Building component manufacturing e.g. electrical controls; joinery; prefabrication of rooms, etc.	
	Building component assembly e.g. placing concrete; laying bricks, installing curtain walling, applying paint, fixing joinery etc.	

1.3	What is the postal address of your organisation's Head Office?	....

1.4	What is your name; your job title; and the department which you work in?	....

1.5	What is your telephone number?	....

1.6	What is your E-mail address?	....

2.	**BUSINESS INFORMATION**
	Please follow the completion instructions for each question in this sub-section

2.1	Please write one ✓ in one column to indicate how your organisation's *MINIMUM LEAD TIME* has changed, if at all, during the past three years.		
	Reduced	No change	Increased

2.2	Please write one ✓ in one column to indicate how your organisation's *MINIMUM TIME TO FULFIL AN ORDER* has changed, if at all, during the past three years.		
	Reduced	No change	Increased

2.3	Please write one ✓ in one column to indicate how your organisation's *FIXED COSTS IN RELATION TO ITS FINANCIAL TURNOVER* has changed, if at all, during the past three years.		
	Reduced	No change	Increased

2.4	Please rank (1st, 2nd, 3rd only) *which of the approaches listed below have been used within your organisation* during the past 3 years.	
	Change management programme (e.g. business process re-engineering)	
	Concurrent design (e.g. designing components and production processes simultaneously)	
	Process definition tools (e.g. flowcharting)	
	Quality Assurance procedures (e.g. ISO 9000)	
	Rapid process changes to address operational needs	
	Strategic planning (e.g. establishing Vision, Goals, Mission and Strategies)	
	Total Quality Management (system to continuously improve quality of goods / services)	
	Other (please specify):	

3.	**DESIGN INFORMATION**
	Please follow the completion instructions for each question in this section

3.1	Please write one ✓ in one column to indicate *what type(s) of personnel, if any, do your design work.*			
	Not carried out	Internal only	External only	Internal and external

3.2	Please write one ✓ in one column to indicate *what type(s) of resources, if any, are used to do your design work*				
	Not carried out	Manual equipment	2D software	3D software	Analysis software

3.3	In the list below, please rank (1st, 2nd, 3rd only) *the types of organisations, (if any), your own organisation has collaborated with during the past three years when introducing your own components / services.*	
	Design consultants e.g. architects / structural engineers / electrical engineers / interior designers etc.	
	Construction consultants e.g. project managers / construction managers etc.	
	Cost consultants e.g. quantity surveying etc.	
	Material processors e.g. aluminium extruders; concrete suppliers; timber processors etc.	
	Building component manufacturers e.g. manufacturers of electrical controls; joinery; curtain walling; room modules etc.	
	Building component assemblers e.g. ground workers; bricklayers, curtain walling installers, painters, joiners etc.	
	Plant businesses e.g. factory machinery manufacturers; site equipment manufacturers, site equipment suppliers etc.	
	NB If no organisations, write one ✓ in this box→	

4.	SUPPLY CHAIN INFORMATION
	Please follow the completion instructions for each question in this section

4.1	In the list below, please rank (1st, 2nd, 3rd only) *the types of organisations (if any) that have introduced new components / services in the past three years which have made it easier for your organisation to carry out its own work*	
	Design consultants e.g. architects / structural engineers / electrical engineers / interior designers etc.	
	Construction consultants e.g. project managers / construction managers etc.	
	Cost consultants e.g. quantity surveying etc.	
	Material processors e.g. aluminium extruders; concrete suppliers; timber processors etc.	
	Building component manufacturers e.g. manufacturers of electrical controls; joinery; curtain walling; room modules etc.	
	Building component assemblers e.g. ground workers; bricklayers, curtain walling installers, painters, joiners etc.	
	Plant businesses e.g. factory machinery manufacturers; site equipment manufacturers, site equipment suppliers etc.	
	NB If no organisations, write one ✓ in this box→	

4.2

Please indicate, by writing one ✓ in the appropriate space in each row, the extent to which you disagree or agree with the statements below.

Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree
Lack of building standardisation makes it difficult for suppliers of construction components and services to learn how construction performance can be improved through their design input.				
Current approaches to building procurement make it difficult for suppliers of construction components and services to work together to improve the construction process.				
There are often communication barriers between organisations involved in the construction project process				

D.3 Schedule Design

D.3.1 Covering letter and follow-up letter

The purpose of the covering letter was to indicate the context of the questionnaire, to assure confidentiality, and encourage reply. The covering letter was composed by the author, but was printed on Contractor-X's headed paper. The letter title, "Egan Report" Questionnaire, was suggested by Contractor-X to make the questionnaire of interest to its recipients. As described in Chapter 2, the Egan Report (DETR, 1998) is the most recent government report addressing the need for the productivity and quality of building production be improved. After two weeks the responses to the questionnaire stalled at forty-two percent, accordingly a follow-up letter was sent out. This second letter was similar to the first but included the sentence: "We would value your input and therefore encourage you to complete the questionnaire". Subsequently, responses rose to forty-eight percent.

D.3.2 Section 1: Identification information

In the first section of the questionnaire, respondents were asked for details about their organisation. As Contractor-X already held extensive data about the organisations involved, the questions asked were sufficient to ensure an accurate match of respondents to existing information. The other purpose of this section was to introduce the respondents to the classifications: consultants, manufacturers and assemblers.

D.3.3 Section 2: Business Information

The main purpose of the second section of the questionnaire was to determine whether respondents carried out concurrent design within their organisations. Contractor-X believe that asking a simple "yes or no" question would be likely to result in respondents offering the "politically correct" response of "yes". This was because Contractor-X thought that the questionnaire would be seen as some kind of vetting exercise by the respondents. Accordingly, the author devised a more sophisticated question which involved the ranking of three options from eight. However, the author recognised that whilst this more sophisticated question might elicit more realistic answers, it could also lead to misunderstandings and, as a result, inaccurate answers. This concern was justified when during piloting it became apparent that the question had to be read several times to be understood. Accordingly, the wording of the question was refined. Subsequent examination of returned questionnaires revealed that the question was completed incorrectly by only one respondent. S/he had ticked several options rather than ranking three of them.

The other three questions in this section sought to measure business performance. This was done to help determine whether there is a need for DFM application. As with the remainder of the questionnaire, closed questions were preferred to open questions. This was because whilst open questions may be easier to ask, they are more difficult to answer, and still more difficult to analyse (Oppenheim, 1992). Also, the author had reached an agreement with Contractor-X that follow-up interviews would be carried out to explore questions in more depth.

D.3.4 Section 3: Design information

The purpose of this section was to determine to what extent, if any, organisations carried out design work, and whether they did so in collaboration with other organisations. Again, rather than asking "yes or no" questions, more sophisticated questions were devised. This was seen as essential by Contractor-X's Head Office personnel, because they had sent out questionnaires in the past which had resulted in them gaining an overly favourable impression of respondents. They were particularly keen to ensure that respondents should understand that negative responses were just as acceptable as positive responses.

D.3.5 Section 4: Supply Chain Information

The purpose of this section was to find out about the respondents' perceptions of their supply chains. The question concerning the introduction of new components / services was the most difficult to word, and was the last to be finalised. However, once again, all but one of the respondents were able to understand the question. Of the three attitude statements contained in this section the first proved the most difficult to word. As with the rest of the questionnaire, the author sought to adhere to design guidelines such as clearly phrase questions and make them easy to answer (Oppenheim, 1992).

D.4 Analysis of Responses

Responses were analysed using the Release 7.0 of the Statistical Package for the Social Sciences (SPSS). Responses to questions such as, *what type(s) of personnel, if any, do your design work* were analysed using the Summarise Frequencies function of SPSS. This function generates tables which show the analysis of respondents' answers. Figure D.1 shows the table generated by SPSS for manufacturers' responses to above question.

Figure D.1: Manufacturers' responses to question 3.1

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	2.00	9	36.0	36.0	36.0
	3.00	1	4.0	4.0	40.0
	4.00	15	60.0	60.0	100.0
	Total	25	100.0	100.0	
Total		25	100.0	100.0	

The numbers shown in the first column of the table are those given to responses options by the author. These are shown in Figure D.2 below. When Figure D.1 is read in conjunction with this figure it shows that thirty-six percent of manufacturers indicated that they have internal design personnel only (i.e. response option ②).

Figure D.2: Example of numbering of response options

3.1	Please write one ✓ in one column to indicate *what type(s) of personnel, if any, do your design work.*			
	①	②	③	④
	Not carried out	Internal only	External only	Internal and external

Each response option in the questionnaire was numbered by the author to facilitate the inputting of responses into SPSS. The response option numbered ⑦ does not appear in the first column of the table shown in Figure D.1 because no respondents ticked that response option in the questionnaire.

The second column of the table shown in Figure D.1 contains the number of responses to each option. For example, nine respondent manufacturers indicated that their organisations use internal personnel only to carry out their design work.

The third column indicates that those nine responses are thirty-six percent of the twenty-five manufacturers who responded to the whole questionnaire. If only twenty-four of the twenty-five respondent manufacturers had answered this question, then the "Total" cell at the bottom of the third column would read "96" rather than "100" (i.e.{100/25 = 4} x 24 = 96).

The fourth column indicates that nine responses is thirty-six percent of the responses to this particular question. To return to the previous example, if there had been only twenty-four responses to this question, then nine responses would have been shown as being thirty-seven and a half percent in the fourth column (i.e.{100/24 = 4.17} x 9 = 37.5). The "Total" cell at the bottom of the fourth column always reads "100". The fifth and final column indicates the cumulative of the percentages shown in the fourth column.

Questions such as, *which of the approaches listed below have been used within your organisation* during the past 3 years ", were also analysed using the Summarise Frequencies function.

However, the analysis of attitude statements in question 4.2 was more challenging. The author sought to rank their responses to the different statements in terms of the extent to which respondents agreed / disagreed with them using three non-parametric statistical tests. These tests do not make assumptions about the underlying nature of distributions and are appropriate for application to data in ordinal scales. For example, a pre-defined ordinal scale ranging from 5 = strongly agree to 1 = strongly disagree was used for the attitude statements contained in question 4.2. Within this scale, a respondent may rank responses to the first attitude statement as 4 (agree) and the second attitude statement as 5 (strongly agree) without indicating exactly how much more he actually agrees with the second question.

Firstly, to obtain a preliminary mean ranking scale of importance, responses were analysed according to the Kruskal-Wallis 1-Way test. This non-parametric test discovers whether differences among the responses to different statements signify genuine population differences, or merely change variations as are expected among several random samples from the same population. The 99% confidence level was adopted as the required statistical significance in order for further analysis to be carried out. Having obtained overall rankings of responses to attitude statements, paired comparisons were then carried out using the Mann-Whitney U - Wilcoxon Rank Sum W test. This non-parametric test is used to determine whether two independent groups have been drawn from the same population. A 95% confidence level was adopted during this analysis to determine significant rank mean differences between individual pairs. Finally, Wilcoxon Matched-Pairs Signed

Ranks testing was carried out for each statement by relating actual responses to the median response (i.e. 3). Further, details of these three tests are provided in the fourth section of Appendix F.

D.5 Research Training

The questionnaire was the most exacting stage of the author's research training. Simple guidelines about questionnaire design provided by research texts proved to be extremely difficult to put into practice. Eight piloting iterations with personnel provided by Contractor-X were needed before the questionnaire could be completed at the first attempt. Subsequently, the administrative effort involved in preparing and posting over two hundred and fifty questionnaires, sending out follow-up letters, coding responses and inputting them into was SPSS was very demanding. Although the selection of appropriate statistical tests was an interesting exercise, the actual analysis of data using SPSS was highly repetitive requiring concentration rather than intellectual effort. It was this part of the research more than any other which made the author realise how much effort is required to gather some research data and analysis it.

E.0 QUESTIONNAIRE FOLLOW-UP INTERVIEWS

E.1 Introduction

The field survey reported in Chapter 4 comprised two sets of structured interviews and one postal questionnaire supported by follow-up interviews. This appendix provides details about the follow-up interviews. A sample of the interview schedule is presented, and the design of the schedule is discussed. Also, the contribution of the questionnaire follow-up interviews to the author's research training is described.

E.2 Sample Interview Schedule

Literature survey findings suggest that the success of existing DFM methodologies in the manufacturing industry relies on the concurrent design within and between businesses. Analysis of questionnaire responses suggests that although there is investment in design personnel and design equipment in the construction industry, there is little design concurrent design activity. The purpose of the follow-up interviews was to gather further information about building design activities. This was considered necessary to inform comparison with the design activities associated with DFM.

The interviews were carried out with a purposive sample of fifteen industry practitioners. These were different people to those who had participated in previous interviews. However, the same mix of occupations was sampled and, again, all the interviewees were directly employed by Contractor-X or worked with Contractor-X during construction projects.

The interviews were conducted by the author at two of Contractor-X site offices: one in Yorkshire and one in Worcestershire. All of the interviewees were involved in the design or construction of the buildings where the site offices were located. Each interview lasted for forty-five minutes, and a day was spent at each location. All the interviewees' organisations had completed and returned a questionnaire.

Again, three of the interviewees were architects. The two interviewed at the Worcestershire site office were junior architects, whilst the architect interviewed at the site office in Yorkshire held a more senior position. A senior consulting engineers was interviewed at each of the two site offices. Five of the interviewees were directly employed by Contractor-X. The project manager at the Yorkshire site was interviewed. The design co-ordinator, the commercial manager, a construction manager, and a Mechanical and Electrical (M&E) services manager were interviewed at the Worcestershire site.

In addition, three interviewees at the Worcestershire site were employed as site managers by three companies which provide M & E, wall, and floor components. At the Yorkshire site, two interviewees were employed as site managers by two companies involved in the construction of substructures and superstructures.

Please note, that although the sample interview schedule shown below refers to prompts cards, for brevity these have been omitted. In these interviews, the prompts cards were almost identical to the relevant schedule pages.

OPENING STATEMENT

Thank you for taking time to participate in this interview. I shall begin by asking you for some information about your organisation. Then, I shall move on to some questions about supply chain issues. After the interview there will be a few minutes for clarification of any issues which are of particular interest to you.

Trials of this interview have been carried out to make sure that it can be completed in half an hour. Your interview answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals. Please note that all interviewees are asked the same questions in the same way, and there are no "right" or "wrong" answers to any of the questions.

SHOW THE INTERVIEWEE PROMPT CARD ONE

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q1	*WHICH ACTIVITY WHICH MAKES THE LARGEST CONTRIBUTION TO YOUR ORGANISATION'S FINANCIAL TURNOVER*	
Consultancy e.g. architectural design / engineering design / construction management / quantity surveying etc.		
Building component manufacturing e.g. electrical controls; joinery; prefabrication of rooms, etc.		
Building component assembly e.g. placing concrete; laying bricks, installing curtain walling, applying paint, fixing joinery etc.		
PROBE	*PLEASE GIVE SOME EXAMPLES OF YOUR ORGANISATION'S MAIN GOODS AND/OR SERVICES*	

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SHOW THE INTERVIEWEE PROMPT CARD TWO

Q2	*WHICH APPROACH HAS BEEN USED MOST IN YOUR ORGANISATION DURING THE PAST 3 YEARS*	
Change management programme (e.g. business process re-engineering)		
Concurrent design (e.g. designing components and production processes simultaneously)		
Process definition tools (e.g. flowcharting)		
Quality Assurance procedures (e.g. ISO 9000)		
Rapid process changes to address operational needs		
Strategic planning (e.g. establishing Vision, Goals, Mission and Strategies)		
Total Quality Management (system to continuously improve quality of goods / services)		
Other (please specify):		
PROBE	*WHY WAS THIS APPROACH CHOSEN?*	

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Q3	*WHAT TYPE(S) OF PERSONNEL, IF ANY, DO YOUR DESIGN WORK.*		
Not carried out	Internal only	External only	Internal and external

Q4	*WHAT TYPE(S) OF RESOURCES, IF ANY, ARE USED TO DO YOUR DESIGN WORK*			
Not carried out	Manual equipment	2D software	3D software	Analysis software

Q5	*HOW IS YOUR ORGANISATION'S CONTRIBUTION TO BUILDING DESIGN USUALLY MANAGED?*
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Q6	*WHAT TYPE OF DESIGN INFORMATION DO YOU NEED TO BE ABLE TO IMPROVE BUILDING CONSTRUCTION?*
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SHOW THE INTERVIEWEE PROMPT CARD THREE

Q7	*WHAT TYPE OF ORGANISATION (IF ANY) DOES YOUR OWN ORGANISATION COLLABORATE WITH MOST WHEN INTRODUCING YOUR OWN NEW COMPONENTS / SERVICES?*	
Design consultants e.g. architects / structural engineers / electrical engineers / interior designers etc.		
Construction consultants e.g. project managers / construction managers etc.		
Cost consultants e.g. quantity surveying etc.		
Material processors e.g. aluminium extruders; concrete suppliers; timber processors etc.		
Building component manufacturers e.g. manufacturers of electrical controls; joinery; curtain walling; room modules etc.		
Building component assemblers e.g. groundworkers; bricklayers, curtain walling installers, painters, joiners etc.		
Plant businesses e.g. factory machinery manufacturers; site equipment manufacturers, site equipment suppliers etc.		
No organisations		
PROBE	**(NB *If interviewee answers "no organisations" go to second probe)*** *WHY DO YOU THINK YOUR ORGANISATION COLLABORATES MOST WITH ....(type of organisation selected by interviewee) WHEN INTRODUCING NEW COMPONENTS / SERVICES?*	
....		
PROBE	*WHY DO YOU THINK YOUR ORGANISATION DOES **NOT** COLLABORATE WITH OTHERS WHEN INTRODUCING NEW COMPONENTS / SERVICES?*	
....		

CONTINUE TO
SHOW THE INTERVIEWEE PROMPT CARD THREE

Q8	*WHAT TYPE OF ORGANISATION (IF ANY) HAS INTRODUCED NEW COMPONENTS / SERVICES WHICH HAVE MADE IT EASIER FOR YOUR ORGANISATION TO CARRY OUT ITS OWN WORK?*	
Design consultants e.g. architects / structural engineers / electrical engineers / interior designers etc.		
Construction consultants e.g. project managers / construction managers etc.		
Cost consultants e.g. quantity surveying etc.		
Material processors e.g. aluminium extruders; concrete suppliers; timber processors etc.		
Building component manufacturers e.g. manufacturers of electrical controls; joinery; curtain walling; room modules etc.		
Building component assemblers e.g. groundworkers; bricklayers, curtain walling installers, painters, joiners etc.		
Plant businesses e.g. factory machinery manufacturers; site equipment manufacturers, site equipment suppliers etc.		
No organisations		

PROBE	**(NB *If interviewee answers "no organisations" go to second probe)*** *IN WHAT WAY HAVE NEW COMPONENTS / SERVICES INTRODUCED BY* .... *(type of organisation selected by interviewee) MADE IT EASIER FOR YOUR ORGANISATION TO CARRY OUT ITS OWN WORK?*

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PROBE	*WHY DO YOU THINK **NO** ORGANISATIONS HAVE INTRODUCED NEW COMPONENTS / SERVICES WHICH HAVE MADE IT EASIER FOR YOUR ORGANISATION TO CARRY OUT ITS OWN WORK?*

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SHOW THE INTERVIEWEE PROMPT CARD FOUR

Q9	*PLEASE STATE THE EXTENT TO WHICH YOU DISAGREE OR AGREE WITH THE STATEMENTS SHOWN*			
Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree
LACK OF BUILDING STANDARDISATION MAKES IT DIFFICULT FOR SUPPLIERS OF CONSTRUCTION COMPONENTS AND SERVICES TO LEARN HOW CONSTRUCTION PERFORMANCE CAN BE IMPROVED THROUGH THEIR DESIGN INPUT.				
CURRENT APPROACHES TO BUILDING PROCUREMENT MAKE IT DIFFICULT FOR SUPPLIERS OF CONSTRUCTION COMPONENTS AND SERVICES TO WORK TOGETHER TO IMPROVE THE CONSTRUCTION PROCESS.				
THERE ARE OFTEN COMMUNICATION BARRIERS BETWEEN ORGANISATIONS INVOLVED IN THE CONSTRUCTION PROJECT PROCESS.				

Q10	*HAVING CONSIDERED THE ABOVE, WHAT KIND OF INFLUENCE DO YOU THINK YOUR ORGANISATION CAN HAVE ON BUILDING* ***DESIGN****?*

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Q11	*HAVING CONSIDERED THE ABOVE, WHAT KIND OF INFLUENCE DO YOU THINK YOUR ORGANISATION CAN HAVE ON BUILDING* ***PRODUCTION****?*

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INTERVIEW SCHEDULE			PAGE .... OF .....
SUPPLEMENTARY PAGE			
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

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CLOSING STATEMENT

Thank you for taking the time to participate in this interview. Having carefully studied your comments, it may be necessary for me to telephone you for a few minutes to clarify minor details.

As stated at the beginning of the interview, your answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

E.3 Schedule Design

This interview schedule was considerably more sophisticated than those designed earlier in the research. It comprised more questions, probes and prompt cards than previous schedules. In addition, two of the questions included routing instructions. As with the first two sets of interviews, a structured format with numbered questions was used because the questions were well defined by literature survey and subsequent questionnaire design. Also, the interview programme was very tight and the interviews could not be allowed to overrun, particularly as these interviews were programmed to last for forty-five minutes rather than half an hour.

E.4 Research Training

The follow-up interviews provided the author with the opportunity to design questions and structure them within a relatively complex schedule incorporating prompt cards and routing instructions. Developing an interview schedule based on a preceding questionnaire, provided the author with a better understanding into the strengths and weaknesses of each type of research instrument. In this research, the questionnaire yielded numerical data which suggested trends, such as lack of design collaboration, but it was interview responses which provided an insight into how far apart design and production often are in the construction industry. Also, the particular practical challenges of the different types of research instrument was experienced. For example, piloting a questionnaire and adhering to a interview timetable.

F.0 CASE STUDY ATTITUDE STATEMENTS

F.1 Introduction

This appendix provides details about the attitude statements discussed in section 6.3.2. The attitude statements comprised the final part of the postal questionnaire described in Appendix D. In this appendix, a sample of the attitude statements is presented, their design discussed, and the methods used to analyse responses are explained. Also, the contribution of the attitude statements to the author's research training is described.

F.2 Sample Attitude Statements

The purpose of the attitude statements was to find out whether or not the Framework for DFM principles described in Chapter 6 would be seen as beneficial by industry practitioners. Without such evidence, Contractor-X would not proceed with the field trial of DFM principles.

5.	**POTENTIAL BENEFITS FROM SUCCESSFUL INTRODUCTION OF AN EQUIVALENT CONCEPT TO "DESIGN FOR MANUFACTURE"**
	Please read the following statement carefully before answering the questions below

The Egan Report recommends introduction of an equivalent concept to "design for manufacture". Our equivalent involves suppliers and subcontractors meeting with consultants, using standard Workshop guidelines to optimise the cost and performance of individual materials, parts and services. These are then integrated for the maximum benefit of clients. The design information generated during these Workshops is converted into standard data that communicates those material, part and service features which affect costs and benefits and how they do so. These data enable project participants to understand each other's operational requirements. On subsequent projects these data are the base from which participants work together.

When answering all of the following questions,
please indicate, by writing one ✓ in the appropriate space in each row,
the extent to which you disagree or agree with the statements below.

	Introduction will allow the industry to:	Strongly Disagree	Disagree	Neither Disagree nor Agree	Agree	Strongly Agree
5.1	Reduce the number of changes to specifications					
	Avoid inappropriate contractor / supplier selection criteria					
	Improve the flow of information between participants					
	Set more realistic project programmes					

	Introduction will offer opportunities to improve the performance of your organisation by:	Strongly Disagree	Disagree	Neither Disagree nor Agree	Agree	Strongly Agree
5.2	Reducing your minimum lead time					
	Reducing your minimum time to fulfil an order					
	Reducing your fixed costs in relation to financial turnover					

	Introduction will reduce the costs of constructing the building elements listed below.	Strongly Disagree	Disagree	Neither Disagree nor Agree	Agree	Strongly Agree
5.3	Substructure					
	Superstructure					
	Roof					
	Envelope					
	Mechanical & electrical services					
	Finishes					

Thank you for taking the time to complete this questionnaire

F.3 Attitude Statement Design

The content of the attitude statements was partially determined by Contractor-X's procurement personnel. They believed that there were three fundamental problems that needed to addressed by an equivalent of DFM. Firstly, those which they described as, "project problems", such as poor flow of project information. Then, there were problems which they described as "supplier problems", such as long lead times. Most importantly, in their opinion, was the problem of reducing construction costs. The attitude statements were piloted with an architect, a construction manager, a commercial manager, and managers from a supplier and a sub-contractor, all of whom either worked for, or with, Contractor-X. The piloting of the description of the Framework for DFM principles was particularly time-consuming. Eight iterations were required to develop the original statement, which is shown below, into the statement which is included in the questionnaire.

Sir John Egan's Task Force has recommended introduction of an equivalent concept to "design for manufacture". We are committed to working with your organisation to achieve this. This will involve construction project participants meeting and working together for a few hours to use a standard format of design techniques and data. We will help each other to optimise the cost and performance of our individual outputs, and then integrate them for the maximum benefit of clients and end-users. The format which we will use will include standard data which will communicate those material, part and service features which affect costs and benefits and how they do so. These data will bridge the knowledge gaps between different organisations and enable us all to provide materials, parts and services which are co-ordinated with each other's operational requirements.

F.4 Analysis of Responses

As reported in section 3.4.2, the questionnaire was posted to a purposive sample of two hundred and sixty-seven practitioners, from whom a total of 127 (48%) responses were received. As described in Appendix D, responses were analysed using the Release 7.0 of the Statistical Package for the Social Sciences (SPSS). A pre-defined ordinal scale, ranging from 5 = strongly agree to 1 = strongly disagree, was used for all the attitude statements, and three non-parametric tests were applied to responses.

Firstly, to obtain a preliminary mean ranking scale of importance, responses were analysed according to the Kruskal-Wallis 1-Way test. This is a test of the null hypothesis that three or more samples are drawn from the same parent population. A null hypothesis is one which is to be tested against another, but is to be nullified in favour of the alternative, subject to a given level of error. The significance level is the probability of rejecting a true null hypothesis in a statistical test (Porkess, 1988). In this case, a significance level of 1% was adopted.

Figure F.1 shows the table generated by SPSS for the attitude statements relating to the cost of constructing building elements. This indicates that the null hypothesis is rejected and that the samples are not drawn from the same population.

Figure F.1: Kruskal-Wallis Test for questions 25 to 30			
RESPONSE	25	126	324.34
	26	126	428.38
	27	125	447.12
	28	125	502.28
	29	125	525.53
	30	126	488.71
	Total	753	

The first column shows question numbers. For purposes of analysis, 25 to 30 are the numbers given to the attitude statements in question 5.3 by the author. This is because the statement about the cost of constructing substructures is the twenty-fifth question to be analysed in the questionnaire. The second column of the table indicates the number of responses to each question. In this case, there were one hundred and twenty-six responses to questions 25, 26 and 30, and one hundred and twenty-five respondents to questions 27, 28 and 29. The total number of responses to this set of questions is seven hundred and fifty-three. The third column indicates that responses were highest (in terms of the ordinal scale of 1 to 5) for question 29 (costs of constructing Mechanical and Electrical services) and lowest for question 25 (costs of constructing substructures).

As Figure F.1 shows, the table generated by SPSS does not present question responses in ranked order, this has to be done manually to facilitate paired comparisons using the Mann-Whitney U - Wilcoxon Rank Sum W test. This tests whether two sampled populations are equivalent and will detect differences in overall distributions rather than differences in the distribution means (Rouncefield and Holmes, 1989). Figure F.2 shows that, applying this test, only responses to question 25 were to significantly different to responses to question 29. Accordingly, responses to question 25 is ranked sixth, and responses to all other questions are ranked equal first.

Figure F.2: Overall sample ranking of construction cost reduction opportunities

Rank	Question	Building element
= 1	29	Mechanical and electrical services
= 1	28	Building envelope
= 1	30	Finishes
= 1	26	Superstructure
= 1	27	Roof
6	25	Substructure

Finally, Wilcoxon Matched-Pairs Signed Ranks testing was carried out for each statement by relating actual responses with the median response. Figure F.3 shows the table generated by SPSS when this test is applied to the attitude statement concerning the cost of constructing M & E (question 29).

Figure F.3: Matched Pairs Test for question 29

VAR00001 - RESPONSE	Negative Ranks	75[a]	a. VAR00001 < RESPONSE
	Positive Ranks	4[b]	b. VAR00001 > RESPONSE
	Ties	46[c]	c. RESPONSE = VAR00001
	Total	125	

In this case, VAR00001 is the median of the pre-determined ordinal scale used for the attitude statements, i.e. VAR00001 = 3. A negative rank occurs where the response is greater than the median, i.e. the response is either agreement (4 on the ordinal scale) or strong agreement (5 on the ordinal scale). Figure F.3 shows that there are seventy-five negatives. This means that there were seventy-five out of one hundred and twenty-five respondents who either agreed, or strongly agreed, that the costs of constructing M & E would be reduced if the Framework for DFM principles were to be introduced. There are only four positives, which means that only four respondents disagreed or disagreed strongly. In this case, responses are significantly greater than the median.

Figure F.4 shows the table generated by SPSS when this test is applied to the attitude statement concerning the cost of constructing substructures (question 25). The table indicates that there were seventy-eight out of one hundred and twenty-five respondents who neither disagreed nor agreed that the costs of constructing sub-structures would be reduced if the Framework for DFM principles were to be introduced. In this case, responses are neither significantly greater than or smaller than the median.

Figure F.4: Matched Pairs Test for question 25

VAR00001	Negative		
-	Ranks	29[a]	a. VAR00001 < RESPONSE
RESPONSE	Positive		
	Ranks	19[b]	b. VAR00001 > RESPONSE
	Ties	78[c]	c. RESPONSE = VAR00001
	Total	125	

F.5 Research Training

The design of attitude statements was the aspect of the research which was most constrained by a research participant. It provided the author with an opportunity to learn how to deal with organisational politics when seeking to carry out research. In this case, the operations function of Contractor-X would not agree to carry out a field trial without evidence of potential support from the consultants, manufacturers and assemblers which it works with. However, procurement personnel felt that it was unreasonable of their operational colleagues to expect them to become involved in the gathering of this evidence.

Procurement personnel believe that it was <u>their</u> credibility which would suffer if the author's research was seen as misguided by other organisations. Moreover, they believed that it would be their operational colleagues who would "get the glory" if the research resulted in improved performance by Contractor-X. As a consequence, there was considerable reluctance to include the attitude statements in the questionnaire. This reluctance was only overcome due to pressure from Contractor-X's most senior personnel. They believed that their company had to be seen to be responding to the Egan Report (DETR, 1998) by the industry's major clients, and saying something about the Report in a questionnaire was a low risk, low cost way of doing so. This episode highlighted to the author that the perceptions of a research proposal within an organisation may sometimes have little to do with its content.

G.0 CASE STUDY INTERVIEW SCHEDULE

G.1 Introduction

This appendix provides details about the semi-structured interviews discussed in section 6.4.1. A sample of the interview schedule is presented, and the design of the schedule is discussed. Also, the contribution of these interviews to the author's research training is described.

G.2 Sample Interview Schedule

The purpose of these semi-structured interviews was to gather opinions about the designs of the assisted bathrooms. All ten interviews were carried out by the author at Contractor-X's Site Offices during one working day. Interviews were carried out consecutively, with one interviewee at a time, and lasted approximately thirty minutes each. All of the interviewees had either been involved in the design of the assisted bathrooms, or were going to be involved in their construction and were already conversant with the design. Contractor-X's project manager was interviewed, as was the senior project architect. The remaining eight interviewees were representatives from the companies which were responsible for the following activities: screeding floors, laying vinyl floor coverings, erecting partitions, placing vinyl wall coverings, fixing suspended ceilings, installing electrical equipment, plumbing in shower etc., and installing ventilation equipment. All these representatives had a trade background and were now employed as supervisors.

OPENING STATEMENT

Thank you for taking the time to participate in this interview. During the interview, I will ask you some questions about the assisted bathrooms which are going to be constructed at this healthcare facility.

Trials of this interview have been carried out to make sure that it can be completed in half an hour. Your interview answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

Please note that all interviewees are asked the same questions in the same way, and there are no "right" or "wrong" answers to any of the questions. After the interview there will be a few minutes for clarification of any issues which are of particular interest to you.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q	*PLEASE TELL ME YOUR OPINIONS ABOUT THE DESIGN FOR THE ASSISTED BATHROOMS*

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PROBE	*DO YOU THINK THAT ALL THE ASSISTED BATHROOMS WILL BE CONSTRUCTED RIGHT FIRST TIME EVERY TIME?*

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

PROBE	*WHICH ASSISTED BATHROOM DESIGN DETAIL DO YOU THINK WILL BE THE EASIEST TO CONSTRUCT, AND WHY?*

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PROBE	*WHICH ASSISTED BATHROOM DESIGN DETAIL DO YOU THINK WILL BE THE HARDEST TO CONSTRUCT, AND WHY?*

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INTERVIEW SCHEDULE			PAGE .... OF .....
SUPPLEMENTARY PAGE			
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

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CLOSING STATEMENT

Thank you for taking the time to participate in this interview. Having carefully studied your comments, it may be necessary for me to telephone you for a few minutes to clarify minor details.

As stated at the beginning of the interview, your answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

G.3 Schedule Design

At the time of these interviews, the author had designed and used the three interview schedules detailed in Appendices B, C and E. All of those schedules had a fully structured format. This was because of three factors: the very focused nature of the questions to be asked, the volume of questions to be asked, and the author's lack of experience as a research interviewer. When designing this schedule, the author felt sufficiently confident to carry out interviews without a fully structured format. Also, there was only one question to be answered, and it was of a more exploratory nature than those asked in previous interviews. Accordingly, the author devised the question and three probes in advance, but did not stick rigidly to their sequence or wording during the interviews. This degree of flexibility was required to elicit meaningful responses from interviewees who were often initially reluctant to state their true opinions because of fear of suffering adverse consequences. Another challenge of designing this schedule was avoiding the use of a leading question, such as "what do you think is wrong with the design of the assisted bathrooms?"

G.4 Research Training

This set of interviews provided the author with the opportunity to design a schedule which seeks to explore one question in depth. Using the schedule with ten industry practitioners provided the author with experience of carrying out semi-structured interviews. Almost every interview followed the same pattern, with little opinion being volunteered at the beginning, then, after hearing the probes and reassurances about confidentially, a barrage of information being offered.

H.0 CASE STUDY QUESTIONNAIRE

H.1 Introduction

This appendix provides details about the anonymous questionnaire discussed in section 6.6.2. A sample of the questionnaire is presented and its design is discussed. Also, the contribution of the questionnaire to the author's research training is described.

H.2 Sample Questionnaire

The anonymous questionnaire was completed by the ten people who attended the assisted bathroom design co-ordination meeting during which DFM principles were applied. The purpose of this questionnaire was to gather the attendees' opinions about the meeting. The questionnaire was designed to obtain answers which had not been composed so as to be "politically correct". Accordingly, the questionnaires were completed in the meeting room, with only the ten attendees present, immediately after the meeting had finished. The attendees were given fifteen minutes to complete the questionnaires, and they were asked to leave the questionnaires on the meeting room table before leaving. After all of the attendees had left the room, the author collected the completed questionnaires from the meeting room table.

ANONYMOUS FEEDBACK QUESTIONNAIRE

Please read the following statement carefully before answering the questions below

This meeting had two major objectives, firstly to develop better design details, and secondly to develop a better format for future meetings. We want to reduce the duration of these meetings and the number of participants who have to be involved. We need accurate feedback to help us do this.

Firstly, please indicate, by writing one ✓ in the appropriate space in each row, the extent to which you disagree or agree with the statements below.
Then, write any suggestions, which you may have about how the meeting format could be improved, in the space provided below.
Please leave your questionnaire on the table after you have completed it.
Thank you for your time.

Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree
The meeting was an effective way for other organisations to learn how their actions can increase our company's costs.				
During the meeting, I developed improved working relationships with other organisations.				
During the meeting, I learnt about other organisations' operational problems				

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H.3 Schedule Design

H.3.1 Opening statement

The opening statement was piloted with Contractor-X's Head Office personnel. The author considered piloting with Site Office personnel but felt that this would provide them with the opportunity to "rehearse" their answers before taking part in the meeting. This could have affected their response to the meeting, and would have created two groups of respondents, those who had prior knowledge of the questionnaire and those who did not. With only ten meeting attendees, this could resulted in groups of responses which were too small to draw any conclusions from.

H.3.2 Attitude statements

Similarly, the attitude statements were piloted with Contractor-X's Head Office personnel. Attitude statements were included to provide a method of obtaining feedback from attendees who might have to hurry to another appointment immediately after the meeting and hence might not have time to answer an open question. The attitude statements dealt with potential organisational outcomes from the meeting. Contractor-X's Head Office personnel were particularly keen to find out whether the arrangement of further meetings would be viewed positively by the attendees. An ordinal scale was used (5 = strongly agree, 1 = strongly disagree) for the statements. Responses were not analysed using SPSS because, with only ten respondents and three statements, sufficient analysis could be carried out using simple arithmetic. Accordingly, ordinal ratings for each statement were added together, then divided by the number of responses to give the mean.

H.3.3 Open question

Asking attendees to write any suggestions which they may have about how the meeting format could be improved was an open question. These types of questions set the subject area, but do not restrict the content of the reply. They are often difficult and time-consuming to analyse. However, in this case where there is a maximum of ten respondents, analysis is a manageable task for a single researcher. Only four attendees had time to answer the open question, all the others had to leave for other appointments or deal with operational problems which had arisen. Those who did have time to answer the question, all advocated that any future meetings should have a longer duration. One respondent suggested that the only way to achieve this would be by having a pre-meeting evening session at a hotel.

H.4 Research Training

The design of this questionnaire had to address the problem of how to gather anonymous feedback from respondents who were known to the author, and were physically near to him. In this case, the questionnaire was not designed until after the practical arrangements concerning the meeting room had been made. Only then was it was possible for the author to write the relevant instructions into the questionnaire. The design of this questionnaire also had to address the problem that respondents might well be in a hurry to leave. The use of attitude statements was proven to be appropriate as only four out of ten attendees had time to answer the open question. By this stage of the research, the author had designed several survey instruments, and the design of this schedule was relatively straightforward, requiring only one piloting iteration.

J.0 CASE STUDY OBSERVATION SCHEDULE

J.1 Introduction

This appendix provides details about the observation schedule discussed in section 6.7.2. A sample of the schedule is presented, the design of the schedule is discussed, and the method used to measure inter-observer agreement is explained. Also, the contribution of the observation schedule to the author's research training is described.

J.2 Sample Observation Schedule

The schedule was used by two non-participant observers at the assisted bathroom design co-ordination meeting where DFM principles were applied. Non-participant observation was used to counteract observer bias by the author. This is a threat to research reliability which may arise when a single researcher is observing alone and has vested interested in the outcome of the research. The purpose of the schedule was to minimise observer errors such as attributing an observed behaviour to the wrong person. In this case, the observers were asked to record when any attendee was <u>not</u> participating in the meeting. The observers were also asked to record the start and finish time of each meeting period.

OBSERVATION SCHEDULE										
PERIOD No.				START TIME						
DURATION (in minutes)	IDENTIFICATION LETTERS OF MEETING ATTENDEES *(At every duration interval write ✗ on the letter which represents any attendee who is NOT PARTICIPATING in the meeting)*									
2	A	B	C	D	E	F	G	H	J	K
4	A	B	C	D	E	F	G	H	J	K
6	A	B	C	D	E	F	G	H	J	K
8	A	B	C	D	E	F	G	H	J	K
10	A	B	C	D	E	F	G	H	J	K
12	A	B	C	D	E	F	G	H	J	K
14	A	B	C	D	E	F	G	H	J	K
16	A	B	C	D	E	F	G	H	J	K
18	A	B	C	D	E	F	G	H	J	K
20	A	B	C	D	E	F	G	H	J	K
22	A	B	C	D	E	F	G	H	J	K
24	A	B	C	D	E	F	G	H	J	K
26	A	B	C	D	E	F	G	H	J	K
28	A	B	C	D	E	F	G	H	J	K
30	A	B	C	D	E	F	G	H	J	K
32	A	B	C	D	E	F	G	H	J	K
34	A	B	C	D	E	F	G	H	J	K
36	A	B	C	D	E	F	G	H	J	K
38	A	B	C	D	E	F	G	H	J	K
40	A	B	C	D	E	F	G	H	J	K
42	A	B	C	D	E	F	G	H	J	K
44	A	B	C	D	E	F	G	H	J	K
45	A	B	C	D	E	F	G	H	J	K
FINISH TIME					COMPLETED BY					

NB	**PARTICIPATING IS:** Time spent focused on the design details, i.e. analysing, clarifying, developing, evaluating, explaining, listening, refining and/or selecting design details

J.3 Schedule Design

Observational methods range from unstructured participant observation to structured non-participant observation. The former is often used for exploratory research, and can generate qualitative records based on observers' memories of events. In contrast, the latter is often used to answer well-defined narrow research questions, and can generate quantitative records based on observers' entries into coded schedules. The main advantage of all observational methods is their directness compared to methods such as questionnaires and interviews. This is because instead of asking people what they do in a particular situation, the researcher can actually see what they do. However, the main disadvantage is that people may not behave as they normally would if they are conscious of being observed. Even where observation was being used as a supplementary research method, it is necessary to minimise this disadvantage. Accordingly, the following statement was made to the meeting attendees by the author:

You will notice that there are two people in the room who will not be participating in the meeting. They are here to take some notes about how effective the meeting format is. Afterwards, I will use their notes to improve the meeting format. Also, at the end of the meeting you will be provided with an anonymous questionnaire which will enable you to record any criticisms and/or suggestions which you may have.

The purpose of this statement was to prevent the attendees feeling that they were being observed for "correct" behaviour and so increase the chance of them behaving "naturally" from the outset. When making statement like this, ethical issues have to be taken into account. Clearly, deceiving research participants is unacceptable practice, particularly, if the research could cause them harm. Throughout the meeting, the non-participant observers did not interact with the participants.

Another difficulty with observational methods is classifying different types of behaviour so they are seen in exactly the same terms by all observers. In this case, the only type of behaviour recorded was, attendees not participating in the meeting. Discussions with the two observers prior to the meeting led to agreement of the definition of participation in the meeting shown on the observation schedule: time spent focused on the design details, i.e. analysing, clarifying, developing, evaluating, explaining, listening, refining and/or selecting design details.

As only one type of behaviour was being recorded, interval coding was used rather than event or state coding. These two alternatives types of coding require the observer to record a variety of events or different states as and when they occur. In contrast, interval coding is triggered by time rather than by events. The observation period is divided into a number of intervals, in this case, two minutes in duration.

Another major challenge is ensuring that observed behaviours are attributed to the people who make them. To achieve this the coding scheme must be easy for the observers to use. In this case, consecutive letters were used to identify each attendee. This scheme was used to avoid confusion with time intervals. For example, reference to minute four could be confused with the fourth attendee if numbers had also been used to identify people. Further, to facilitate consistent recording of observations, the attendees were asked always to sit in the same places around the table throughout the meeting.

J.4 Measuring Inter-observer Agreement

Inter-observer agreement is the extent to which two or more observers obtain the same results when measuring the same behaviour. High levels of inter-observer agreement suggest that the data obtained from a structured observation schedule is reliable. Cohen's Kappa is a measure of inter-observer agreement which corrects for chance agreement. The three steps followed to calculate Kappa for the data obtained using this observation schedule are shown below.

- *Calculate the proportion of agreements* (P_0). This is given by:

  number of agreements / (number of agreements + number of disagreements)

  which in this case is: 809 / (809 + 111) or $P_0 = 0.88$

An agreement takes place when both observers record the same behaviour category on the same occasion. A disagreement takes place when they record a different behaviour category on the same occasion.

- *Calculate the proportion expected by chance* (P_C). This is given by multiplying the number of times the first observer records a category of behaviour by the number of times the second of observer records the same category of behaviour. The number of times a category of behaviour is recorded is expressed as a percentage of the total number of observations made by each observer. In this case, there was only one type of behaviour categorised: non-participation at the meeting. In this case, the first observer recorded non-participation on 249 occasions and the second observer recorded non-participation on 263 occasions. Expressed as percentage of the 920 total observations made by each observer these figures are .28 and .29 respectively. Multiplied together these give a P_C of 0.0812.

- *Calculate Cohen's Kappa (K)*. This is given by the formula:

$$K = \frac{P_0 - P_C}{1 - P_C}$$

In this case,

$$K = \frac{0.88 - 0.0812}{1 - 0.0812} = 0.87$$

Fleiss (1981) has suggested that a Kappa of above 0.75 is excellent. However, common sense suggests that inter-observer agreement is likely to be higher when there are only two observers than were there are many observers. Further, Taplin and Reid (1973) have suggested that observers perform best when they know that they are being monitored. In this case, the observers were monitored by the author.

J.5 Research Training

The case study provided the author with the opportunity to design a structured observation schedule, and subsequently analyse the data recorded by two non-participant observers. The main lesson learned was that it may not always be possible to operationalise a research question which intuitively seems to be appropriate. In this case, the question which the author arrived at intuitively was: when are attendees participating in the meeting? This seemed appropriate and was included in all the drafts of the observation schedule. However, during it became apparent during piloting that the observers could spend too much time recording participation and not have sufficient time to observe. As a result the question to be answered by this research instrument was amended to, when are attendees not participating?

K.0 Validation Interviews for DFM Strategies

K.1 Introduction

This appendix provides details about the validation interviews discussed in section 7.7.1. A sample of the interview schedule is presented and the design of the interview schedule is discussed. Also, the contribution of the interviews to the author's research training is described.

K.2 Sample Interview Schedule

Each strategic plan for successful application of DFM principles was presented to seven industry practitioners simultaneously during structured interviews carried out by the author in a meeting held at the one of the participants' offices. In order to facilitate validation of the strategies, a thorough explanation of their content was provided for the interviewees. A presentation covering the classification, formulation, application and success of rules and metrics was made by the author. The presentation was based around eleven diagrams which are shown in Figures 7.1 to 7.11. For brevity, these eleven figures are referred to, not reproduced, here. The interview schedule was different to all those designed previously during the research because, rather than being completed by the author as interviewer, it was used as a workbook by the interviewees. The schedule included all the diagrams used by the author in the presentation. This approach was taken to ensure that the interviewees had a good understanding of DFM issues before assessing the strategies, and to provide them with information which they could refer to whilst carrying out their assessments.

As shown in the sample schedule below, at the end of each part of the presentation interviewees were asked questions. After the interviewees had completed their answers, the author asked them whether they had sufficient understanding of the information provided so far to be able to move on to the next part of the presentation. When necessary, the author clarified diagram details for the interviewees.

The interviews involved a purposive sample of seven participants. Two are building designers, two are construction managers, and three are employed by companies which design, manufacture, supply and/or place or install building components. As discussed in Chapter 7, this sample comprised representatives from organisations which have been trying, without success, to implement DFM. All of the interviewees hold senior positions, and three are company directors.

OPENING STATEMENT

Thank you for taking the time to participate in this meeting. During the meeting, the following information will be presented:

1. definition of DFM principles;
2. description of key factors concerning the classification, formulation, application and success of DFM principles;
3. outline of individual DFM application strategies for five specific types of construction organisations.

Throughout the meeting, you will be asked for your opinion about the information provided. Your answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

Please note that there are no "right" or "wrong" answers to any of the questions. After the meeting there will be a few minutes for clarification of any issues which are of particular interest to you.

1. Definition of DFM principles

DFM has been applied successfully to many different types of goods, including aircraft, cars, computers and toys. The results of application have often been quite remarkable. For example, 90% reductions to assembly times; and 50% reductions in production costs.

The fundamental principles of DFM are:

- standard production design improvement rules, and
- standard production design evaluation metrics.

These are applied during design to improve the success of production.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q1	*ARE YOU ALREADY USING STANDARD PRODUCTION DESIGN IMPROVEMENT RULES AND EVALUATION METRICS IN YOUR ORGANISATION?*

If yes, please give recent practical examples in the space provided below

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*If **no**, please state why you have not done so.*

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2. Key issues concerning DFM principles in construction

2.1 Issues concerning the classification of rules and metrics

During this part of the meeting, the diagrams shown in Figures 7.1 to 7.6 were presented to the interviewees.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q2	*DO YOU THINK A COMPREHENSIVE SUMMARY OF CLASSIFICATION ISSUES HAS BEEN PROVIDED?*
If yes, please identify where more clarification would be useful	
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*If **no**, please state which aspects of classification have not been addressed*	
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2.2 Issues concerning the formulation of rules and metrics

During this part of the meeting, the diagrams shown in Figures 7.7 to 7.8 were presented to the interviewees.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q3	*DO YOU THINK THAT THE CLASSIFICATION OF CONSTRUCTION ORGANISATIONS SHOWN IS VALID?*
....	

Q4	*DO YOU THINK THAT THE RANGE OF CONSTRUCTION ORGANISATIONS SHOWN IS COMPREHENSIVE?*
....	

Q5	*DO YOU AGREE WITH THE DESIGN INFLUENCE SHOWN FOR DIFFERENT ORGANISATIONS?*	*YES / NO*
*If **no**, please state what levels of design influence you think different construction organisations have*		
....		

2.3 Issues concerning the application of rules and metrics

During this part of the meeting, the diagrams shown in Figures 7.9 to 7.10 were presented to the interviewees.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q6	*DO YOU AGREE WITH THE DESIGN AUTHORITY SHOWN FOR DIFFERENT ORGANISATIONS?*	*YES / NO*

*If **no**, please state what levels of design authority you think different construction organisations have*

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2.4 Issues concerning the success of rules and metrics

During this part of the meeting, the diagram shown in Figure 7.11 was presented to the interviewees.

Q7	*DO YOU AGREE WITH THE METHODS SHOWN FOR THE DIFFERENT ORGANISATIONS?*	*YES / NO*
*If **no**, please state what productivity and quality improvement methods you think are possible for the different construction organisations*		
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3. Strategies for successful application of DFM principles

During this part of the meeting, the five strategies for successful application of DFM principles were presented to the interviewees.

INTERVIEW SCHEDULE			PAGE .... OF .....
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

Q8	*DO YOU THINK THAT THE STRATEGIES ARE TECHNICALLY FEASIBLE AND ECONOMICALLY VIABLE*	
STRATEGIES	*YES*	*NO*
DFM strategy for building designers		
DFM strategy for construction managers		
DFM strategy for standard component designers / producers		
DFM strategy for bespoke component producers / installers		
DFM strategy for component installers		

For each strategy, if yes, please identity the parts of the strategy which you think would be most difficult to achieve and state why.

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*For each strategy, if **no**, please identify the part(s) of the strategy(s) which you think could not be achieved and state why.*

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INTERVIEW SCHEDULE			PAGE .... OF .....
SUPPLEMENTARY PAGE			
INTERVIEWEE		JOB TITLE	
ORGANISATION		DATE	

CLOSING STATEMENT

Thank you for taking the time to participate in this meeting. Having carefully studied your comments, it may be necessary for me to telephone you for a few minutes to clarify minor details.

As stated at the beginning of the interview, your answers will remain confidential and only summary results will be made available, without any reference to specific organisations or individuals.

K.3 Schedule Design

Previous schedules had been designed to elicit responses about interviewees' existing experiences and knowledge. In contrast, this schedule was designed to find out interviewees' opinions about new information immediately it was presented to them. The content of the schedule was determined by the need to provide interviewees with a copy of the new information to refer to whilst answering questions. The structure of the schedule was determined by the need to guide the interviewees step-by-step through its content. The use of the schedule was determined by its volume, which meant it took several hours to work through. This precluded individual interviews, and necessitated a group interview approach.

K.4 Research Training

The final interviews provided the author with the opportunity to design questions and structure them within a hybrid schedule which included presentation information. Using this schedule as part of a quite lengthy presentation to seven senior industry practitioners provided the author with advanced experience of field survey work. These final interviews were very different to those first carried out by the author two years earlier, because rather than having to be persuaded to give information, interviewees were keen to receive information from the author, and were happy to have the opportunity to offer their opinions about it. The interviewees' perception of the author, based on his publications, as an expert made the group meeting with seven interviewees easier to manage than early individual interviews had been.

L.0 PUBLICATION STRATEGY

L.1 Introduction

Several publications by the author were referred to in Chapter 8. In this appendix, the author's overall publication strategy is defined, the selection of journals for research dissemination is described, and full publication references are listed. In addition, the contribution of journal writing to the author's research training is discussed.

L.2 Overall Strategy

The author's publication strategy is to disseminate specific research findings to particular types of organisations through selected journals. The two objectives of this strategy are:

1) to contribute to productivity and quality improvement in the construction industry; and

2) to instigate opportunities for further research by the author.

L.3 Selection of Journals

The author's first step in the selection of journals was to define the construction organisations which could benefit from the author's research findings. As explained in Chapter 7, DFM principles are relevant to the full range of construction organisations. However, there is no single journal which is aimed at both building companies and building component businesses.

The selection of a journal for disseminating research findings to building component businesses was relatively straightforward. The professional journal, *Manufacturing Engineer*, meets all of the author's five selection criteria:

- readership includes target construction organisations;
- content covers both design and production issues;
- editorial objectives include the dissemination of research findings;
- well respected;
- high editorial standards.

However, the selection of a single journal for disseminating research findings to building companies was not possible. Although there are several magazines which are widely read in the industry, these tend to focus on building construction and do not disseminate research findings. To overcome this problem, the author selected two journals, *the architects' journal* and *Construction Management and Economics*. The *architects' journal* is a professional publication which focuses on building design. It has a technical editor and a specific section for new contributions to building design thinking. *Construction Management and Economics* is a renowned academic journal which publishes original research papers from around the world.

L.4 List of Publications

The exploratory research reported in Chapter 2, provides an in depth analysis of how design affects production options. This information has been disseminated to the construction industry through the following two publications:

Fox, S., Staniforth, I. and Cockerham, G. (2000) Craft Markets. *Manufacturing Engineer*, Manufacturing Division of The Institution of Electrical Engineers, **79** (5), 188 - 191.

Fox, S. and Cockerham, G. (2000) Matching design and production. *the architects' journal*, emap business publications, **211** (9), 50 - 51.

The inductive research reported in Chapter 4, provides an analysis of the relevance of standard production design improvement rules and standard production design evaluation metrics. This information has been disseminated to the construction industry through the following two publications:

Fox, S., and Cockerham, G. (2000) Designing for orders. *Manufacturing Engineer*, Manufacturing Division of The Institution of Electrical Engineers, **79** (2), 63 - 66.

Fox, S. and Cockerham, G. (2000) Designs on construction. *the architects' journal*, emap business publications, **212** (19), 44.

The deductive research reported in Chapter 5, provides building component producers with practical guidance about how to successfully apply rules and metrics within their businesses. This information has been disseminated in the following publication:

Fox, S., Staniforth, I. and Cockerham, G. (1999) World Class Craft. *Manufacturing Engineer*, Manufacturing Division of The Institution of Electrical Engineers, **78** (4), 145 - 148.

The deductive research reported in Chapter 6, provides construction managers with practical guidance about how to successfully apply rules and metrics to buildings. A paper covering this research has been written and is with journal referees.

The strategic plans presented in Chapter 7, provides guidance about rules and metrics for a comprehensive range of construction organisations. This information will be disseminated in the following publication:

Fox, S., Marsh, L. and Cockerham, G. (2001) Design for manufacture: a strategy for application to buildings. *Construction Management and Economics*,

As indicated by the editor's letter overleaf, this paper was accepted in January 2001.

L.5 Research Training

Submitting to three different journals provided the author with the opportunity to develop the skill of writing for different types of readers. This is an essential requirement for the wide dissemination of research findings. Each journal provides different writing challenges. In the author's opinion, *Manufacturing Engineer* occupies the middle ground between the strict academic rigour of *Construction Management and Economics*, and the more journalistic approach of *the architects' journal*. For example, submissions to the *architects' journal* should not exceed one thousand words, and may be altered by the editor who does not send proofs to authors. In contrast, manuscripts of up to five thousand words can be submitted to *Construction Management and Economics.* These will be subject to refereeing before being considered by its editors. Subsequently, print proofs have to be approved by the author. Although writing for journals has been extremely demanding, the research has benefited as a result. For example, the research reported in Chapter 7 was possible because participants had read some of the author's publications.