CRANFIELD UNIVERSITY

School of Industrial and Manufacturing Science

(Quality & Process Improvement Department)

PhD THESIS

Academic Year 1999-2000

Jonathan Morris

Improving Construction Design: The Lean Thinking Paradigm

Supervisor: Professor J.H. Rogerson

September 1999

Cranfield
UNIVERSITY

[BLANK PAGE]

EXECUTIVE SUMMARY

A study has been conducted into improving construction design through the application of the lean thinking paradigm. Its objective was to identify the issues relating to design efficiency and how a lean thinking approach might address these issues. The investigation consisted of examining work already undertaken in the field by other researchers to identify the state of the art. The change order request system was examined to gain first insights into waste in construction design, and to gauge the size of the opportunity for the application of lean thinking. An Electronic Data Gathering Tool (EDGT) was then developed to allow further exploration of the design decision making process at the system / sub-system level. The EDGT was used on three live construction projects. From the data recorded a design planning tool, Design Decision Planner (DDP), was created to help improve control of the design process and lead to a more standardised approach to construction design. Standardising the approach to product development is an important component of lean thinking.

The main recommendations for making construction design lean are:

1. Use DDP to plan and improve control of the design decision making process, assign design responsibility and to make the process more transparent.

2. Measuring progress against planned design is a useful process metric.

3. Improve the designer's cost and programme visibility when choosing between design options.

4. Redefine the role of the quantity surveyor from cost controller to value for money assessor. The role needs to be better integrated into the design process to reach its full potential.

5. Need to develop more rigorous methods of assessing the buildability of design options. This problem could be eased in the short-term by incorporating construction professionals into the early design phases.

6. Designers need to use more process reason drivers when choosing between design options, not just functional criteria.

7. The change order request system could be redesigned to identify the root causes of contract issue design changes and, hence, improve the design decision making process.

[BLANK PAGE]

ACKNOWLEDGEMENTS

I would like to express my gratitude to a number of people, without whom, this thesis would never have been written. Firstly, to my supervisor John Rogerson for his guidance and encouragement, to Graham Jared and Ian Cox for their continual technical and moral support, to Harold Stevens, Peter Griffiths, Robert Light and Peter Santesson for providing with me so much of their time and insights into construction design, and the project's industrial partners for allowing me access to personnel and data: Liam Boyd (Stanley Bragg Partnership), Mike Elks (Taylor Woodrow Management Contracting), Huw Thomas (Sir Norman Foster and Partners), Gary Long (WSP Consulting Engineers), Stuart Alexander (WSP Consulting Engineers) and Tony Tidy (Pluswall). I would also like to thank EPSRC and DETR for their financial support under grant GR/K62699, 'The Development of Decision Making Tools for Controlled Innovation in Construction'. Finally, I would like to thank those people whose names will not be mentioned who contributed some thought, suggestion or insight which helped me along the way.

Jonathan Morris, September 1999

[BLANK PAGE]

"Happy are those who find wisdom, and those who get understanding, for her income is better than silver, and her revenue better than gold." **Proverbs 3: 13 – 14.**

To Lynne for her constant love and patience and to my
parents for all their encouragement and support.

[BLANK PAGE]

GLOSSARY

BAA	British Airports Authority
BM	Bench Marking
BPM	Building Project Model
BPR	Business Process Reengineering
CAD	Computer Aided Design
CE	Concurrent Engineering
CIP	Commercially Important Persons
Con	Constructability
COR	Change Order Request
DDP	Design Decision Planner
DETR	Department of the Environment, Transport and Regions
DFA	Design For Assembly
DFD	Design Function Deployment
DFM	Design For Manufacture
DLE	Davis Langdon & Everest
DSM	Design Structure Matrix
EDGT	Electronic Data Gathering Tool
EPA	Environmental Protection Agency
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
GDP	Gross Domestic Product
GUI	Graphical User Interface
IDAC	Integration in Design and Construction
IDL	International Departures Lounge

IMI	Innovative Manufacturing Initiative
IT	Information Technology
JRP	JR Preston
OAP	Ove Arup & Partners
PPC	Percentage of Planned Activities Completed
QA	Quality Assurance
QFD	Quality Function Deployment
RIBA	Royal Institute of British Architects
SBP	Stanley Bragg Partnership
SNFP	Sir Norman Foster & Partners
TPS	Toyota Production System
TQM	Total Quality Management
TWMC	Taylor Woodrow Management Contracting
US	United States
VE	Value Engineering
VM	Value Management

THESIS OUTLINE

Chapter 1: Delineating the Research

The first chapter of the thesis introduces the research topic, namely the application of lean thinking to construction design, and attempts to contextualise it in the current research and market trends. The objectives of the project are defined and a section on the novelty of the work is also included.

Chapter 2: The Lean Thinking Paradigm

This is the first part of the literature survey. It focuses on the definition of lean thinking and how it has already been applied to construction. It also considers other process improvement techniques such as concurrent engineering and business process reengineering because of their similarity to lean thinking. Particular emphasis is placed upon how lean thinking has been applied to construction design.

Chapter 3: The Creativity Enigma: Design in Construction

Chapter 3 forms the second part of the literature survey. It attempts to provide some insights into design research in general with particular emphasis on construction design. Included are treatises on psychological / sociological aspects of design, macro design models and approaches to design.

Chapter 4: Research Outline

This chapter provides an overview of the research approach that was used to meet the objectives specified in chapter 1. It includes an explanation of why the case study approach was taken and the logic behind the successive data gathering exercises. This chapter provides a brief synopsis of the entire thesis.

Chapter 5: Identifying Waste in Construction Design

In chapter 5, change orders are identified as a type of waste in construction design. Details are provided of an investigation of the change order request system. It outlines the four case studies investigated, how the data was collected and processed, and what was found from the study. The results are then related back to the general theme of the application of lean thinking to construction design.

Chapter 6: Electronic Data Gathering Tool

On the basis of the results of the change order request system, it was decided that it was necessary to map the design decision making process at the system / sub-system level for a number of live construction projects. Chapter 6 provides details of the design and development of an electronic data gathering tool that was used to capture data about design decision making.

Chapter 7: Mapping the Design Decision Making Process

The data recorded by the electronic data gathering tool was analysed to see what insights about design decision making could be made and how this might lead towards a 'leaner' construction design process. Chapter 7 provides details of the data recorded, how it was analysed and what findings were made. The findings are then related back to the application of lean thinking to construction design.

Chapter 8: Towards Lean Design: Design Decision Planner (DDP)

From the results of mapping the design decision making process it was realised that design planning is generally quite poor in construction projects. It was also realised that a large part of the construction design decision making process is generic. This led to the development of a tool to help plan design which has been called Design Decision Planner (DDP). Chapter 8 provides details of the theory of the tool and how it can be used in construction projects.

Chapter 9: Significance of the Results

This chapter summaries the main findings of the research and evaluates the work against the objectives set in chapter 1. Recommendations are made to take the first steps towards making construction design lean and the value of the work is considered on the basis of short-term gains for industry, and the long-term gains for the deposit of knowledge.

Chapter 10: Recommendations for Further Work

The final chapter suggests avenues that require further study in order to make construction design leaner.

Figures and Tables

Figures and tables have been numbered with respect to the order in which they appear in each chapter, for instance, table 5.3 is the third table to appear in chapter 5. If the first character is alphanumeric this refers the reader to the relevant appendix, for example, figure G.4 indicates figure four in appendix G.

CONTENTS

EXECUTIVE SUMMARY III

ACKNOWLEDGEMENTS V

GLOSSARY IX

THESIS OUTLINE XI

CONTENTS XIII

LIST OF FIGURES XVII

LIST OF TABLES XX

CHAPTER 1 DELINEATING THE RESEARCH 1
1.1 THE CONSTRUCTION PREDICAMENT 2
1.2 MANUFACTURING APPROACH 3
1.3 RESEARCH THEMES 5
  1.3.1 Construction Design 5
  1.3.2 Lean Thinking 5
1.4 OBJECTIVES 6
1.5 THE NOVELTY OF THIS WORK 6

CHAPTER 2 THE LEAN THINKING PARADIGM 9
2.1 INTRODUCTION 10
2.2 LEAN THINKING 10
  2.2.1 Origins 10
  2.2.2 The Principles of Lean Thinking 11
  2.2.3 Why Lean: Benefits of Implementing Lean Thinking 15
  2.2.4 Lean Design 16
2.3 THE CONCURRENT ENGINEERING AND BUSINESS PROCESS REENGINEERING (BPR) CONNECTION 17
  2.3.1 Concurrent Engineering 18
  2.3.2 Business Process Reengineering (BPR) 19
2.4 PROCESS IMPROVEMENT IN CONSTRUCTION 21
2.5 LEAN THINKING IN CONSTRUCTION DESIGN 24
  2.5.1 Conceptual Foundations 24
  2.5.2 Methodologies / Models 27
  2.5.3 Design Tools / Metrics 28
2.6 CONCLUSIONS 33

CHAPTER 3 THE CREATIVITY ENIGMA: DESIGN IN CONSTRUCTION 37
3.1 INTRODUCTION 38
3.2 PSCHOLOGYICAL & SOCIOLOGICAL PERSPECTIVES OF DESIGN 43
    3.2.1 Introduction 43
    3.2.2 Design Models 44
    3.2.3 Protocol Analysis 45
    3.2.4 Sociological Perspective 46
3.3 MACRO DESIGN MODELS 47
    3.3.1 RIBA 48
    3.3.2 BAA 49
    3.3.3 Process Protocol 50
    3.3.4 Other Models 52
3.4 AXIOMATIC DESIGN 52
3.5 DESIGN FOR MANUFACTURE (DFM) / DESIGN FOR ASSEMBLY (DFA) 54
3.6 CONSTRUCTION DESIGN METHODS / APPROACHES 54
    3.6.1 Constructability 54
    3.6.2 Value Engineering / Value Managment 57
3.7 CONSLUSIONS 58

CHAPTER 4 RESEARCH OUTLINE 61
4.1 FROM THE LITERATURE SURVEY... 62
4.2 IDENTIFYING WASTE IN CONSTRUCTION DESIGN 62
4.3 ELECTRONIC DATA GATHERING TOOL (EDGT) 64
4.4 MAPPING THE DESIGN DECISION MAKING PROCESS 64
4.5 DESIGN DECISION PLANNER 65
4.6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK 65
4.7 RECONCILING RESEARCH TO THE LEAN THINKING PARADIGM 65

CHAPTER 5 IDENTIFYING WASTE IN CONSTRUCTION DESIGN 69
5.1 INTRODUCTION 70
5.2 OBJECTIVES 71
5.3 CHANGE ORDERS 71
5.4 THE CHANGE ORDER REQUEST SYSTEM 72
5.5 ANALYSIS OF CHANGE ORDER REQUEST DATA 74
5.6 OVERVIEW OF THE CASE HISTORIES 75
5.7 CHANGE ORDER REQUEST RESULTS FOR CRANFIELD UNIVERSITY LIBRARY 80
5.8 CHANGE ORDER REQUEST RESULTS FOR HEATHROW CARGO WAREHOUSE 94
5.9 CHANGE ORDER REQUEST RESULTS FOR MARKS & SPENCER PRESTON 104
5.10 DISCUSION 109
    5.10.1 Change Order Costs to Project 109
    5.10.2 Why Change Orders Occur: Process Inefficiencies 110
    5.10.3 The Work Package Dimension 113

5.10.4 Cumulative Count and Cumulative Cost of Change Orders 114
5.10.5 Other Issues 115
5.11 CONCLUSIONS 116
5.12 SUMMARY 117

CHAPTER 6 ELECTRONIC DATA GATHERING TOOL 119
6.1 INTRODUCTION 120
6.2 INITIAL INVESTIGATION 121
6.2.1 Objective of the Interviews 121
6.2.2 Interview Format 121
6.2.3 Issues Arising From Interviews 122
6.2.4 Conclusions 124
6.3 OBJECTIVES 125
6.4 TOOL DESIGN 126
6.4.1 Theory 126
6.4.2 Information Fields 127
6.4.3 Systematisation 133
6.5 USING THE ELECTRONIC DATA GATHERING TOOL 134
6.5.1 Implementation / Anticipated Use 134
6.5.2 *'Actual'* Data Collection 134
6.5.3 Data Gathering Tool Limitations 135
6.5.4 Improving the Data Gathering Tool 136
6.6 DISCUSSION 137

CHAPTER 7 MAPPING THE DESIGN DECISION MAKING PROCESS 139
7.1 INTRODUCTION 140
7.2 OBJECTIVES 140
7.3 CASE STUDY DESCRIPTIONS 141
7.3.1 Chelmsford 141
7.3.2 Gatwick 143
7.3.3 Bourne 144
7.3.4 Comparison 146
7.4 DESIGN PLANNING 152
7.5 DATA PROCESSING 153
7.5.1 Matching Data 154
7.5.2 Decisions Superseded 155
7.5.3 The Design Period 155
7.6 VALUE GENERATION: DECISION COMMONALITY AND CHRONOLOGY ... 155
7.7 DEFINING THE DISCIPLINES 163
7.8 WITHIN THE LIMITS: CONSTRAINTS & SELECTING DESIGN OPTIONS 167
7.9 COST & PROGRAMME VISIBILITY 174
7.10 WHERE DECISIONS WERE MADE 177
7.11 INFORMATION NEEDS / SOURCES 179
7.12 INFORMATION TECHNOLOGY SUPPORT 181
7.13 THE ROLE OF THE DESIGN MODEL 184

7.14 DISCUSSION 186
7.14.1 Design and the Design Process 186
7.14.2 Generic Design: Standardising The Design Approach 187
7.14.3 Design Team Interaction 189
7.14.4 Constraints and Reason Drivers 190
7.14.5 Cost & Programme Visibility 191
7.14.6 Design Support 192
7.14.7 SWOT Analysis: Research Approach 193
7.15 CONCLUSIONS 194
7.16 SUMMARY 196

CHAPTER 8 TOWARDS LEAN DESIGN: DESIGN DECISION PLANNER (DDP) .. 199
8.1 INTRODUCTION 200
8.2 OBJECTIVES 200
8.3 THEORETICAL BASIS 200
8.4 DESIGN DECISION PLANNER (DDP) METHODOLOGY 203
8.5 WORKED EXAMPLE 205
8.6 IMPLEMENTATION 209
8.7 SYSTEMATISATION 210
8.8 CONCLUDING REMARKS 211

CHAPTER 9 SIGNIFCANCE OF THE RESULTS 213
9.1 MEETING THE OBJECTIVES 214
9.1.1 The Application of Lean Thinking Principles to Construction Design 214
9.1.2 Potential Benefits of Lean Construction Design 214
9.1.3 Recommendations for Construction Design to Become Lean 215
9.2 RESEARCH ACHIEVEMENTS / MAIN FINDINGS 216
9.2.1 From the Change Order Request Analysis (Chapter 5) 217
9.2.2 Developing the Electronic Data Gathering Tool (EDGT) (Chapter 6) 217
9.2.3 From the Mapping of the Design Decision Making Process (Chapter 7) 218
9.2.4 Developing Design Decision Planner (DDP) (Chapter 8) 218
9.3 THE VALUE OF THIS WORK 219

CHAPTER 10 RECOMMEDATIONS FOR FURTHER WORK 221
10.1 FURTHER STEPS ON THE ROAD TO LEAN DESIGN 222

REFERENCES 225

BIBLIOGRAPHIC INFORMATION 234

APPENDICES A - K

LIST OF FIGURES

Figure 2.1 – Theoretical approach to design (Isatto & Formoso,1998) 26
Figure 4.1 – Research Stages and the Lean Thinking Paradigm 67
Figure 4.2 – Research Components and Their Respective Chapters in this Thesis . 68
Figure 5.1 - Project Team Procedures Manual (Section 13): Monitoring and Issuing of Works Contractor Instructions 73
Figure 5.2 – Distribution of Change Order Costs: Cost Class Intervals of £500 80
Figure 5.3 – Change Order Costs: Reason & Originator 84
Figure 5.4 – Change Order Costs: Work Package & Originator 86
Figure 5.5 – Change Order Costs: Work Package & Reason 87
Figure 5.6 – Number of Change Orders Specifying Each Reason Category 88
Figure 5.7 – Number of Change Orders Affecting Each Work Package 88
Figure 5.8 – Fractional Cost of Change Orders for Each Work Package 89
Figure 5.9 – WP 3010: Substructure and Concrete Frame 90
Figure 5.10 - WP 5010: Blockwork / Partitions 91
Figure 5.11 – WP 4010: Roof Steelwork and Perimeter Columns 92
Figure 5.12 – WP 4030: Curtain Walling 92
Figure 5.13 – WP 7010: Mechanical Services 93
Figure 5.14 – Distribution of Change Order Costs: Cost Class Intervals of £500 94
Figure 5.15 – Change Order Costs Associated With Each Reason Category 96
Figure 5.15a – Change Order Costs: Work Package & Reason (WP 10010-1 – WP 4035-2) 98
Figure 5.15b – Change Order Costs: Work Package & Reason (WP 4035-3 – WP 9020) 99
Figure 5.16a – Fractional Cost of Change Orders for Each Work Package (WP 10010-1 – WP 4035-2) 99
Figure 5.16b – Fractional Cost of Change Orders for Each Work Package (WP 4035-3 – WP 9020) 100
Figure 5.17a – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2) 101
Figure 5.17b – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2) 101
Figure 5.18 – WP 3010-1: Substructure 102
Figure 5.19 – WP 7010-2: Building Services – Mechanical 103
Figure 5.20 – WP 5060 Fittings and Furnishings 103

Figure 5.21 – Distribution of Change Order Costs: Cost Class Intervals of £500.... 105
Figure 5.22 – Change Order Costs Associated With Each Reason Category......... 107
Figure 5.23 – Change Order Costs: Work Package & Reason 108
Figure 5.24 – Fractional Cost of Change Orders for Each Work Package.............. 108
Figure 5.25 – Number of Change Orders Affecting Each Work Package 109
Figure 6.1 - Design decisions to be recorded by the data-gathering tool................ 126
Figure 7.1 – Cumulative Count of Decisions Made Against Normalised Time (all three case studies) 156
Figure 7.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) – Chelmsford 157
Figure 7.3 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) - Gatwick... 158
Figure 7.4 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) – Bourne 158
Figure 7.5 – Gatwick & Chelmsford Design Decisions Made Against Normalised Time 160
Figure 7.6 – Chelmsford & Bourne Design Decisions Made Against Normalised Time 161
Figure 7.7 – Gatwick & Bourne Design Decisions Made Against Normalised Time 162
Figure 7.8 – Who Made the Design Decisions (Chelmsford) 163
Figure 7.9 – Who Made the Design Decisions (Gatwick) 164
Figure 7.10 – Who Made the Design Decisions (Bourne)...................................... 164
Figure 7.11 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Chelmsford) 165
Figure 7.12 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Gatwick).. 165
Figure 7.13 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Bourne)... 166
Figure 7.14 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Chelmsford)................ 169
Figure 7.15 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Gatwick) 170
Figure 7.16 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Bourne) 170
Figure 7.17 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Chelmsford)... 172
Figure 7.18 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Gatwick) 173
Figure 7.19 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Bourne) 173
Figure 7.20 – Designer's Cost Visibility (Chelmsford)... 175

Figure 7.21 – Designer's Cost Visibility (Gatwick) 176
Figure 7.22 – Designer's Cost Visibility (Bourne) 176
Figure 7.23 – The Types of Meetings Where Design Decisions Were Made (Chelmsford) 177
Figure 7.24 – The Types of Meetings Where Design Decisions Were Made (Gatwick) 178
Figure 7.25 – The Types of Meetings Where Design Decisions Were Made (Bourne) 178
Figure 7.26 – Percentage of Design Decisions Using Particular Information Source Types (Chelmsford) 180
Figure 7.27 – Percentage of Design Decisions Using Particular Information Source Types (Gatwick) 180
Figure 7.28 – Percentage of Design Decisions Using Particular Information Source Types (Bourne) 181
Figure 7.29 – Percentage of Design Decisions Using Particular Information Technology Types (Chelmsford) 182
Figure 7.30 – Percentage of Design Decisions Using Particular Information Technology Types (Gatwick) 183
Figure 7.31 – Percentage of Design Decisions Using Particular Information Technology Types (Bourne) 183
Figure 7.32 – Percentage of Design Decisions Occurring in Each RIBA Stage (Chelmsford) 184
Figure 7.33 – Percentage of Design Decisions Occurring in Each BAA Stage (Gatwick) 185
Figure 7.34 – Percentage of Design Decisions Occurring in Each RIBA Stage (Bourne) 185
Figure 7.35 – SWOT Analysis on Research Approach 194
Figure 8.1 – Cumulative Count of Decisions Made Against Normalised Time (all three case studies) 201
Figure 8.2 – Cumulative Count of Design Decisions to be Made Against Normalised Time 201
Figure 8.3 – Distribution of Design Decisions to be Made Against Normalised Time 202

LIST OF TABLES

Table 1.1 – Construction Task Force Goals (Construction Task Force, 1998) 3
Table 2.1 – Improvements Made at the Wiremold Company Through the Application of Lean Thinking 16
Table 2.2 – Process Improvement Research in Construction 23
Table 3.1 – Research into Design 41
Table 5.1 - The Professional Team for Each Case History 76
Table 5.2 – The Availability of Data for Each Case History (Time is Either by Day or Month) 77
Table 5.3 – Case Study Profiles: Cranfield University Library and Heathrow Cargo Warehouse 78
Table 5.4 – Case Study Profiles: Marks & Spencer Preston and Aylesbury Shopping Centre 79
Table 5.5 - Work Package Costs and Timings for Cranfield University Library 81
Table 5.6 - Frequency of Change Orders Affecting One or More Work Package 82
Table 5.7 – Reason Categories Available for Cranfield University Library Case Study 83
Table 5.8 – Total Change Order Costs for Each Reason Category 85
Table 5.9 – Percentage of Change Order Costs Due to Process Issues 86
Table 5.10 - Work Package Costs and Timings for Heathrow Cargo Warehouse 95
Table 5.11 – Total Change Order Costs for Each Reason Category 97
Table 5.12 – Total Change Order Costs Due to Process Issues 97
Table 5.13 – Frequency of Change Orders Affecting More than One Change Order 104
Table 5.14 – Work Package Costs for Marks & Spencer Preston 106
Table 5.15 – Total Change Order Costs for Each Reason Category 107
Table 5.16 – Percentage of Change Order Costs Due to Process Issues 107
Table 5.16 – Change Order Costs as a Percentage of the Total Project Cost 110
Table 5.17 – Most Costly Reason Categories and the Percentage of Change Order Costs Due to Process Issues for Each Case Study 111
Table 5.18 – The Most Costly Work Packages in Terms of Fractional Cost for Each Work Package 113
Table 5.19 – The Most Costly Work Packages in Terms of Absolute Costs of Change Orders Affecting Each Work Package 114

Table 6.1 – Information fields used in the data gathering tool with explanations 132
Table 7.1 – Design Team (Chelmsford) 142
Table 7.2 – Design Team (Gatwick) 144
Table 7.3 – Design Team (Bourne) 145
Table 7.4 – Client Assessment for the Case Studies Used in Design Decision Process Maps 146
Table 7.5 – Design Stage Dates for the Case Studies Used in Design Decision Process Maps 148
Table 7.6 – When Design Team Members Joined the Project (Chelmsford) 149
Table 7.7 – When Design Team Members Joined the Project (Bourne) 150
Table 7.8 – Building Details and Construction Planning Outline for the Case Studies Used in Design Decision Process Maps 151
Table 7.9 – Design Features for the Case Studies Used in Design Decision Process Maps 152
Table 7.10 – Disciplines' of the Data Collectors 153
Table 7.11 – Constraint Category Codes and Descriptions 168
Table 7.12 – Five Most Common Constraint Categories Cited for each Case Study... 169
Table 7.13 – Reason for Selecting Design Options Category Codes and Descriptions 171
Table 7.14 – Five Most Common Reason Categories for Choosing Between Options Cited for each Case Study 172
Table 7.15 - Percentage of Design Decisions Made in Meetings Attended by Single Disciplines / Multidisciplines 179
Table 7.16 – Most Common Types of Information Source Used to Support the Design Decision Making Process in each Case Study 179
Table 7.17 – Most Common Types of Information Technology Used to Support the Design Decision Making Process in each Case Study 181
Table 8.1 – Cumulative 'Target' and 'Lower Boundary' Percentages of Design Decisions to be Completed Over Normalised Time 202
Table 8.2 – Worked Example: The Number of Decisions That Need To Be Completed Over Time 205
Table 8.3 – Worked Example: List of System / Sub-System Level Design Decisions by Split into Appropriate Normalised Time Periods 209

[BLANK PAGE]

CHAPTER 1 DELINEATING THE RESEARCH

"...we are also issuing a challenge to the construction industry to commit itself to change, so that, working together, we can create a modern industry ready to face the new millennium." **Sir John Egan, BAA, Chairman of the Construction Task Force.**

CHAPTER 1 DELINEATING THE RESEARCH 1
1.1 THE CONSTRUCTION PREDICAMENT 2
1.2 MANUFACTURING APPROACH 3
1.3 RESEARCH THEMES 5
1.4 OBJECTIVES 6
1.5 THE NOVELTY OF THIS WORK 6

1.1 THE CONSTRUCTION PREDICAMENT

The construction industry plays a pivotal role in the UK economy. In 1998, it had an estimated output of about £58 billion, which is equivalent to approximately 10% of GDP (Construction Task Force, 1998). The industry employs around 1.4 million people in over 163, 000 different organisations. Within Europe, construction investment is estimated at a round 690 billion ECU, or 12% of GDP, with the industry employing approximately 7% of the European workforce (Proverbs, et al 1999). This makes construction one of the most important industrial sectors in the European Union (EU). The industry effects many people's lives, many more than those directly employed by construction companies, as there is a continued need for a built environment to satisfy the lifestyle demands of modern society. However, despite the great importance of the building community, there is growing discontent amongst construction clients who feel that the industry is under performing. Indeed Fisher (1993) states that a view is held by international clients that UK buildings cost too much for a particular specification. With the globalisation of business activities and the desire to attract foreign investment, this is becoming an increasingly important perspective. Other problems include the predictability of cost and construction time of buildings. The Agile Construction Initiative (1998) found that two thirds of buildings will exceed their cost estimates and three quarters of projects will experience delayed completion.

This notion of deficiency is part of a current trend of dissatisfaction with the industry as a whole. This has been highlighted by two recent reports Latham (1994) and The Construction Task Force (1998) who suggest a range of areas for improvement. According to the latter, there are a number of problems facing the industry that need to be addressed:

- Low profitability
- Lack of investment in R&D and training
- Clients undiscriminating - lowest price
- Client dissatisfaction with contractors performance:
    - Price, time, number and rectification of defects, final quality
- Fragmentation:
    - 163,000 construction companies on DETR register
    - Most employ less than 8 people
- Extensive subcontracting - process issues / continuity
- Need to rethink the product delivery process
- Waste in construction (from recent studies in USA and Scandinavia)
    - 30% of construction is rework
    - Labour efficiency only 40-60% of potential
    - 10% of materials wasted

In response to the perceived problems, The Construction Task Force set what it considered to be both attainable and sustainable goals for the industry.

Performance Indicator	Annual Improvement
Capital Cost	Reduce by 10%
Construction Time	Reduce by 10%
Predictability	Increase by 20%
Defects	Reduce by 20%
Accidents	Reduce by 20%
Productivity	Increase by 10%
Turnover and Profits	Increase by 10%

Table 1.1 – Construction Task Force Goals (Construction Task Force, 1998)

As a means of attaining these goals the report suggests that adopting techniques and lessons learnt from other industries, such as manufacturing, as the way forward. A particular technique indicated as having potential is the 'lean thinking' approach. This is particularly relevant to the areas of the product delivery process, waste in construction and client satisfaction. Indeed, there is evidence to show that manufacturing concepts can be applied to the extremes within the construction industry as some Japanese companies, such as Toyota homes, 'manufacture' rather than construct domestic housing. This has led to significant reductions in lead times and improvements in the management and timing of resource allocation (Gann, 1996).

Latham (1994) suggested that a 30% productivity target should be set for the year 2000. Over the six year period this equates to an annual increase of 5%, or half the Egan target. Latham (1994) also highlighted that the management of the design process is of great importance. Some of the issues he emphasises as effecting successful design management are the creation of detailed check lists of design requirements in the appointment documents of consultants, ensuring the client understands the design proposals, signing off various stages of the design as they are achieved and the avoidance of 'fuzzy edges' at design interfaces. Latham is also strongly in favour of integrating the work of designers and specialists.

1.2 MANUFACTURING APPROACH

In January 1993 there was an end to the EU trade barriers which meant that construction companies could now tender on an equal basis for work in other EU countries (Proverbs et al, 1999). In response to increased competition and the introduction of international players in the domestic market, the construction industry is becoming more proactive in its attempts to improve the total construction process and, hence, the efficiency of its product delivery capability. As part of this focus on process advancement, or 'reengineering', researchers are considering what lessons have been learnt in other industries, especially the manufacturing sector, which might provide solutions to problems in construction. The reason for this focus on manufacturing is evidence from both the automobile and aerospace industries that changes in working practices over the last 10 - 15 years have led to significant improvements in efficiency, productivity and customer focus. Improvements which are seen to be needed in the construction industry (Latham, 1994).

The major change in working philosophy in manufacturing industry has been the adoption of 'process-based' management rather than 'function-based' management. In other words, manufacturing from initial establishment of customer requirements right through to final delivery of the product, is seen as a sequence of processes, including the whole supply chain, which need to be managed and controlled. This change in philosophy, as well as requiring cultural changes in management style, requires the application of tools for managing the processes. It is the application, sometimes with a need for modification, of these manufacturing derived process management tools to the management of construction projects which provides the need for, and focus of, much research at present. In their comparison of manufacturing and construction, Deasley and Rogerson (1997) suggest that the aerospace industry is the most relevant manufacturing sub-sector to construction. They go on to identify areas that are critical to aerospace and have been the subject of much research. These same areas are likely to be critical to construction:

- Supply chain management
- Partnering / partnerships
- Modularization of final products
- Pre-fabrication
- Design for manufacture
- IT Support
- Business process characteristics

Towill (1997) suggests that the success in manufacturing industry is largely due to an increasing awareness of best practice which has led to a reduction in restrictive working practices with rigid skill demarcations, and the adoption of more productive value adding processes.

Interestingly Sanviado & Medeiros (1990) claim that both construction and manufacturing suffer from similar types of problems, which include:

1. The high cost of correcting design errors and including changes late in the design stage or early construction / manufacturing.

2. Duplication of information in the same project, little information sharing, and lack of available planning information.

3. Poor efficiency in moving information from design to construction / manufacturing.

It is in this climate that Engineering and Physical Science Research Council (EPSRC) established Link IDAC (Integration in Design and Construction) and

'Construction as a Manufacturing Process' as part of the Innovative Manufacturing Initiative (IMI) research programme. The work which this thesis is based upon derives from a three year Link IDAC project entitled, 'The Development of Decision Making Tools for Controlled Innovation in Construction' which was carried out by Cranfield University and a number of industrial partners:

- Pluswall (curtain wall contractor)
- Sir Norman Foster & Partners (architectural practice)
- Stanley Bragg Partnership (architectural practice)
- Taylor Woodrow Management Contracting (construction management)
- WSP Group (consulting engineers)

1.3 RESEARCH THEMES

This study is an investigation in the broad area of process improvement. In particular, this work seeks to address the applicability of *lean thinking* to improve construction design.

1.3.1 Construction Design

In the construction industry, design is self-evidently a key process. It is during this phase of a project that the major decisions are taken which determine the shape and size of a building, the type of construction and services, as well as cost and construction time. Indeed, construction design is a problem solving process which cannot always be stated comprehensively at the outset because of the many different interests that have to be satisfied, and the successful outcome of the design process is often determined by the choice of starting point in relation to the definition of the client's problem (Gray et al, 1994). Clearly, the design, as well as conforming to the client's functional specification and being aesthetically satisfying, must be capable of being delivered in as economic and efficient way as possible. Hence, the need to control design innovation without inhibiting architectural integrity or freedom. However, there are suggestions that there is a need to improve the approach to design management in construction. Indeed, Koskela et al, (1997) make the somewhat strong assertion, *'It is not an exaggeration to say that the management of design and engineering is one of the most neglected areas in construction projects'.* Whether neglected or otherwise, it remains a fact that design is perhaps the most influential process in construction projects, one that should be continually reviewed, and modified, to ensure the creation of products that meet the myriad of clients' needs and expectations.

1.3.2 Lean Thinking

Lean thinking is based on a process improvement philosophy originally developed by the Toyota Motor Company in the 1950s. It was inspired by a Toyota engineer called Taiichi Ohno and became known as the Toyota Production System (TPS). The term lean thinking, however, was first used, by Womack and Jones (1996) who took the basic philosophy of TPS and transformed it into a generic process improvement approach with a specific theoretical framework. The kernel of lean thinking is to identify and remove waste from all the processes within an organisation, not just production. This is achieved by identifying what the client *values* and trying to maximise value in the product. Maximising value is accomplished by mapping the *value stream* and then removing all possible activities which do not add value to the product (some non-value adding activities are usually necessary due to current technological limitations). The process activities are then reorganised to allow value generation to *flow* on the basis of the client, and upstream activities, *pulling* value through the process. The authors suggest that the application of this simple approach can lead to dramatic savings in the development and production costs of all commodities. Another benefit is significantly shorter lead times for the time taken to bring a new product to market and delivery of goods to customers.

This study seeks to obtain some of the benefits of lean thinking for the construction design process.

1.4 OBJECTIVES

The objectives of this study are as follows:

1. Apply lean thinking principles to construction design.
2. Assess the potential benefits of lean construction design.
3. Make recommendations on becoming 'lean' (for construction design).

These objectives lead to three key questions:

1. What are the underlying principles of lean thinking?
   (Chapter 2 – Lean Thinking Paradigm)
2. What are the defining characteristics of the design process?
   (Chapter 3 – The Creativity Enigma: Design in Construction)
3. How will the research be undertaken?
   (Chapter 4: Research Outline)

Each of these questions will be addressed in the following three chapters of this thesis.

1.5 THE NOVELTY OF THIS WORK

Work on applying lean ideas to construction started in the early 1990s by Lauri Koskela. The majority of this work has been directed towards production and production planning, which is unsurprising given the origins of the approach.

However, some work has been done within the terms of reference of applying 'lean thinking to the construction design process'. The focus of the work has been with regard to theoretical foundations / concepts, frameworks and the development of tools (see chapter 2). This study set out to use objective data to identify waste in the construction design process and then to investigate *value generation* by mapping the design decision making process at the system / sub-system level. For this purpose, an Electronic Data Gathering Tool (EDGT) was developed to capture the necessary information. On the basis of the data collected an approach to improving design planning and progress monitoring at the system / sub-system level, has been suggested.

The following list is a summary of the novel aspects of this work:

1. The use of objective change order request data to estimate the amount of waste in the design decision making process.

2. The way in which the change order request data was analysed: identifying the reasons why change orders occurred, how they related to process issues and assessing the cumulative effect of change orders on a normalised time basis for each work package.

3. The development of the EDGT to investigate the design decision making process at the system / sub-system level.

4. The EDGT was used on three live construction projects to collect objective data about design decision making. The case studies were assessed to establish the amount of commonality that exists between construction projects at the system / sub system level, the roles of the main disciplines, the cost / programme visibility that designers had when making decisions, the main constraint types impinging upon decision making and the main reason drivers used to choose between design options.

5. The analysis of the data led to recommendations for improving design planning and monitoring of design progress – Design Decision Planner (DDP). This is with a view to applying the concept of 'standardised work' from the lean thinking paradigm.

6. Other issues identified include: The limited cost and programme visibility that designers have when choosing between design options, the designer's limited ability to assess the buildability of design options and the development of the role of the quantity surveyor from cost controller to assessing value for money of each design option.

It should be noted that numbers 1 and 2 had input from Dr Ian Cox, Cranfield University.

Four papers, so far, have been published from the Link IDAC project on which this work is based – 1 refereed journal, 3 refereed conferences:

1. **Cox, I.D., Morris, J.P., Rogerson, J. & Jared, G. (1999)** 'A quantitative study of post contract award design changes in construction'. Construction Management and Economics, vol. 17, no. 4.

2. **Morris, J.P., Rogerson, J. & Jared, G. (1998)** 'A Tool for Modelling the Briefing and Design Decision Making Processes in Construction'. *Proceedings of the ARCOM (Association of Researchers in Construction Management) Fourteenth Annual Conference,* 9th-11th September 1998, University of Reading, UK, pgs. 320-329.

3. **Morris, J.P., Rogerson, J. & Jared, G. (1998)** 'A Quantitative Method for Analysing the Impact of Contract Issue Design Changes in Construction'. *Proceedings of the First International Conference on New Information Technologies for Decision Making in Civil Engineering,* 11th-13th October 1998 Montreal, Canada, pgs. 1197-1208.

4. **Morris, J.P., Rogerson, J. & Jared, G. (1998)** 'Modelling Briefing and the Design Decision Making Process in Construction'. In: *Product and Process Modelling in the Building Industry, Second European Conference on Product and Process Modelling in the Building Industry,* 19th-21st October 1998, BRE Watford, UK, pgs. 365-372.

CHAPTER 2 THE LEAN THINKING PARADIGM

Literature Survey: Part 1

"I come back to this idea of time, quality and cost, and the decision making process depends on what the driver is." **Roger Walker, Director of Stanley Bragg Partnership.**

CHAPTER 2 THE LEAN THINKING PARADIGM 9
2.1 INTRODUCTION 10
2.2 LEAN THINKING 10
2.3 THE CONCURRENT ENGINEERING AND BUSINESS PROCESS REENGINEERING (BPR) CONNECTION 17
2.4 PROCESS IMPROVEMENT IN CONSTRUCTION 21
2.5 LEAN THINKING IN CONSTRUCTION DESIGN 24
2.6 CONCLUSIONS 33

2.1 INTRODUCTION

The research topic was introduced in chapter 1 in broad terms, that is, the application of *lean thinking* to *construction design*. This immediately suggests two fairly distinct aspects of the research, and hence the literature survey:

1. Lean thinking.
2. The design process in the construction industry.

Therefore, for the sake of clarity, the literature survey has been split into two chapters. Chapter 2 (literature survey part 1) explicates lean thinking and chapter 3 (literature survey part 2) deals with design in the construction industry. There is a degree of overlap between subject areas, however, each chapter will deal with the stated topic.

2.2 LEAN THINKING

2.2.1 Origins

The origins of lean thinking lie with Taiichi Ohno in the 1950s. Ohno worked for the Toyota Motor Company where he observed inefficiencies within the production system. On gaining sufficient seniority within the company he began to investigate ways to improve areas that he considered deficient. His approach to improvement became known as the Toyota Production System.

His first observation was that workers spent most of their time watching machines rather than actively participating in the transformation processes. This was necessary so that the worker could stop the machine in the event of a problem occurring - a manual form of process control. From his experience at the Toyota textile plant, Ohno was aware that one man in the textile plant could operate 40-45 looms (Ohno, 1978). In answer to the inevitable question 'why is it that one man in the textile company can operate 40-45 machines and in the motor company one man is only able to operate one machine?', Ohno discovered that it was because the machines in the textile plant stopped automatically when machining was complete, or if the thread broke and began to make defective cloth. With this revelation, Ohno developed limit switches for the motor company machines which allowed one worker to supervise several of them at a time.

Ohno's underlying driving force was the eradication of waste in the production process. Ohno identified several types of waste:

- Over production
- Waiting
- Unnecessary transportation
- Unnecessary process steps
- Inventory – both work in progress and finished goods

- Correcting Mistakes

Five further steps helped to make the Toyota Production System one of the leanest in the world:

Create standard work sheets:
Standard methods for each procedure.

Instilling a team mentality:
Ohno used the analogy of relay racers, the team is only as good as the last hand over. This focused attention on what happens to the product as it moves from one process to the next.

Addressing supply:
Just-in-Time method adopted.

Adopting Kanban:
Kanban used to control the Just-in-Time supply.

Production Levelling:
Use of small lot sizes and machines with small set up times. The first step in production levelling is to divide the number of units required by the number of days to produce them. Daily production is tweaked as necessary.

2.2.2 The Principles of Lean Thinking

The term *lean thinking* was coined by Womack and Jones (1996) and, as such, this section of the literature survey draws heavily upon their work to elucidate the underlying principles and concepts embodied within the approach. As stated in section 2.2.1, the origins of lean thinking originate in the Japanese automobile industry. As Ohno was concerned with the identification and eradication of waste within Toyota's production system, Womack and Jones have built upon this principle, extending it throughout the organisation and beyond into the supply chain.

Waste can be considered to be those activities and processes which *do not* add direct value to a particular product. By removing waste from the total production process, that is all those activities used to produce the article, including design, scheduling, administration, etc, the percentage of value adding activities increases, thus making the organisation more efficient. In their book, 'Lean Thinking', Womack and Jones (1996) suggest an approach for commercial organisations to use to identify and remove waste from their processes. The approach consists of five steps:

1. Specify value by specific product.
2. Identify the value stream for each product.
3. Make value flow without interruptions.
4. Let the customer pull value from the producer.

5. Pursue perfection.

2.2.2.1 Specifying value

Specifying value is the initial step to identifying waste in an organisation's processes. At the heart of this first stage is the assertion that value can only be defined with reference to the ultimate customer (Womack and Jones, 1996). Acharya et al (1995) also take this stance, as does Kelly and Male (1993), with their definition of value management:

"a proactive, creative, problem solving service, using a multi-disciplinary team oriented approach to make explicit the client's value system..."

The concept of value itself is somewhat nebulous. The value of an article is not an intrinsic constant embodied within the product. Value depends on the individual's preferences, the circumstances in which the person finds themselves – i.e. the degree of need that the individual has for the product, the ability of the product to perform its intended task and secondary social effects: how much will other individuals value the product that I have bought and how will that affect me? This latter issue is of particular importance within the construction context. For example, constructing a showcase building as a new company head quarters may enhance the company's profile. However, if that same building is erected on a site with a delicate ecosystem, the same product may bring adverse publicity to the organisation and, therefore, reduce the building's value.

Womack and Jones (1996) go on to say that value must be defined in terms of specific products with specific capabilities, offered at specific prices, through dialogue with specific customers. An addition to the list should be 'at a specific time'. The value of a product is highly time dependent. A customer might be willing to pay £Xs for a service or product to fulfil a particular need right up until the point that a competitor can offer an equivalent service, or product, at a lower price. The perceived value of the original service / product was reduced in a manner beyond the control of the producer. In a lean enterprise a 'target cost' is calculated when developing a product. This is calculated by looking at the current product packages being offered by competitors and working out how much it would cost to create an equivalent 'waste free' product. The difference between the competitor price and the waste free price (which will be lower) can be utilised in two ways: (1) introduce the product into the market at a lower price than the competitor or (2) use the money to incorporate additional functions to differentiate the product from the competitor, and sell at the same price. Interestingly, Ohno (1978) states that a principle of the Toyota Production System is that profit margins are determined by selling price – cost = profit. This is subtly different to the traditional selling price = actual cost + profit, approach. It recognises that in reality the customer sets the price on the basis of the value that is attached to the product, at a particular point in time, within a given market context.

In another definition of value management, Green (1989) supports Womack and Jones' (1996) view that value must be made with reference to the client.

> *"Value management is concerned with defining what 'value' means to a client within a particular context. This is achieved by bringing the project stakeholders together and producing a clear statement of the project's objectives. Value for money can then be achieved by ensuring that design solutions evolve in accordance to agreed objectives."*

However, Green (1989) recognises that the client is only one of the project stakeholders, albeit a very important stakeholder, and that the other stakeholder views must be taken into consideration. A particularly important issue within the construction industry is that Womack and Jones' (1996) 'ultimate customer' is often *not* the client. In construction projects it is common for the end user and the client to be different groups of people within an organisation, or within different organisations. This suggests that a stakeholder approach to specifying value within the context of applying lean thinking to construction, might be the most appropriate.

To fully address the issue of value the whole product needs to be considered through the eyes of the customer. What will the client's experience of the product be? Will the client believe they received value for money?

2.2.2.2 Identifying the value stream

The value stream is all the activities / tasks required to bring a particular product through the three critical management tasks: problem-solving, information management and physical transformation.

Problem-solving:
From concept through detailed design and engineering to production launch.

Information Management:
Order taking through detailed scheduling to delivery.

Physical Transformation:
From raw materials to the finished product in the hands of the customer.

The entire value stream must be identified by mapping for each product, or family of products. This is to help identify where waste exists in the system.

Each of the tasks identified in a given value stream are then classified by the following designations:

1. Tasks which unambiguously add direct value to the product.
2. Tasks which add no value to the product but are unavoidable with current technological limitations of the production processes / technologies.
3. Tasks which add no value to the product and are immediately avoidable.

A key issue to mapping the value stream of a product is that it must go beyond production, through the organisation, and into the supply chain. This means that all activities from concept through detailed design to actual availability, from initial sale, through order entry and production scheduling to delivery, and from raw materials produced to delivery of the product to the customer (Womack and Jones, 1996).

When the value stream has been mapped, all the category 3 tasks should be removed from the total production process.

2.2.2.3 Flow

The third stage is to make the value creating steps flow. This is a departure from the batch and queue approach as used in traditional production, and non-production, processes to a method where individual articles (1 unit of a particular product) flow from one process to the next. Ohno (1978) recalls moving from a process, i.e. functional layout – all lathes together, all grinding machines together, etc, to a product layout – processes in the order in which they are to be performed, to achieve operational flow. An important facilitator to this organisational strategy was the right sizing of machines to the production volume, with quick set up times (Womack and Jones, 1996). Indeed, Ohno demanded three minute die changes from his engineers (Shingo, 1989). Fortuitously for Toyota, a researcher called Shingo had been developing ideas about reducing set up times which he called Single Minute Exchange of Die (SMED). The implementation of SMED to the manufacturing processes contributed to the success of the Toyota Production System (Shingo, 1989).

Coupled with the need to reorganise the production layout, there needs to be a change from a functional departmental structure to a product team set up. This is a crucial aspect of moving towards a lean enterprise. Product teams are responsible for a product, or product family, from concept, through development and marketing, to production and after sales service.

2.2.2.4 Pull

Pull essentially means that no one up stream should produce goods or services until the customer down stream asks for it (Womack and Jones, 1996). ‘Customer’ is used in its widest sense and can be the end user of the product or an ‘internal customer’, which includes the next down stream manufacturing process. The affects of applying lean thinking to a commercial organisation reputedly include reduced production lead times and product development lead times, i.e. from concept to market. This means that the customer is able to ‘pull’ value from the producer much more easily. The customer no longer has to place orders weeks or months in advance for a particular product with ‘anticipated’ needs in mind, but is able to order on the basis of current need. This problem is further accentuated by customers changing the detail of their requirements, and hence order, closer to the time of delivery which leads to considerable amounts of rework. As lead times are cut demand for a particular product becomes more stable. It also means that organisations respond directly to customer demand rather than forecasts of anticipated demand.

2.2.2.5 Perfection

To call this the 'final stage' for implementing lean thinking would be somewhat misleading. This is because the fifth step is intended to be an ongoing process. It can be thought of as the 'return to stage 1' arrow to facilitate 'lean iterations'. According to Womack and Jones (1996), *"It dawns on the individuals involved that there is no end to the process of reducing effort, time, space, cost and mistakes, whilst offering a product that is evermore nearly what the customer actually wants."* This is achieved through a combination of *kaikaku* – radical improvements, and *kaizen* - continuous incremental improvements. That is, there is an ongoing identification of waste in the system which the organisation strives to remove. Development of new technologies for a particular process step may play a significant role here. Removing waste utilising a new technology may remove one type of waste but incorporate a less significant 'new waste'. Future changes may be made to address this waste in the struggle to achieve the goal of 100% value adding activities.

2.2.3 Why Lean: Benefits of Implementing Lean Thinking

According to Womack and Jones (1996), the application of lean thinking to an organisation can have a significant impact by reducing product development lead time, the time from customer order to delivery, the amount of physical space required to manufacture a product, inventories and the number of mistakes made. They cite several examples in detail: Lantech, Wiremold Company, Pratt & Whitney and Porsche. These are a diverse set of manufacturing companies operating in very different markets. Table 2.1 shows the improvements made at the Wiremold Company through the application of lean thinking. Taken at face value, these are highly significant figures which cannot be ignored. The survival of companies depends on their ability to compete in the market place. As more companies begin to implement lean principles it is likely that those who don't respond (or those who don't respond with an alternative approach) will begin to loose market share. It is also claimed that to implement lean thinking costs very little in terms of capital investment. Indeed, if a company finds itself spending significant sums of money, it is likely that it is taking the wrong approach. The time period over which change occurs varies. Some improvements should be seen within the first 6 months, however, to change the mentality of the whole organisation and to see benefits from time invested with suppliers, it is likely to take around five years for a lasting transformation (Womack and Jones, 1996).

Metric	1990 (Before Lean Thinking)	1995 (After Lean Thinking)
Sales per employee ($000s)	90	190
Throughput time to produce average product	4-6 weeks	1-2 days
Product development time	3 years	3-6 months
Suppliers	320	73
Inventory turns	3.4	15.0
Space required (index)	100	50
Sales (index)	100	250
Operating Profit (index)	100	600
Profit sharing (% of straight wage)	1.2	7.8

Table 2.1 – Improvements Made at the Wiremold Company Through the Application of Lean Thinking

2.2.4 Lean Design

Womack and Jones (1996) present a compelling method for improving the efficiency of commercial organisations. Although the authors state that lean thinking should be applied throughout the company and beyond into the supply chain, their examples concentrate largely on the production component. This is perhaps unsurprising as the origins of lean thinking stem from the production system, and this is where the ideas are most easily applied. However, in two of the case studies presented: Porsche and Wiremold Company, a description of changes made to the product development process are incorporated. This is significant for this piece of research as (1) the *total construction process* is more akin to the manufacturing product development process than production (Ballard & Howell, 1998), this is also the view of the author of this thesis, and (2) this research is concerned with the application of lean thinking to construction design. Design is also the subject of an example regarding the manufacture of bicycles.

The common thread between all three examples is the creation of a product team with a clearly defined individual who is responsible for the development of the product. The teams are multi-disciplinary and often include product designers / design engineers, production engineers, purchasing staff (selecting suppliers and contracts for parts), tool engineers (design process machinery), planners and service staff (assist with after sales service). The team is co-located to increase the level of synergy between team members. The team is responsible for all stages of product development including, engineering the product, selecting / making production tools and manufacturing methods. The team should incorporate the 'voice of the customer' into the product. Quality Function Deployment (QFD) is proposed as an effective means of identifying and addressing the needs of the customer, and a means of making design flow. Womack and Jones (1996) also claim that work can be *standardised* so that each new product development project is approached in the same way. Teams are told to aim for a target cost which is determined by estimating a market price (what the market will accept) and subtract an acceptable margin.

Interestingly, in their exploration for links between design and the business excellence model, Oakland & Oakland (1997) suggest that design should incorporate 'process thinking' to lead to an integrated approach to managing people and resources through processes that enable an organisation to realise the full potential of its design capabilities in the pursuit of customer satisfaction. This notion of applying process thinking to design is also supported by Goldschmidt (1992).

2.3 THE CONCURRENT ENGINEERING AND BUSINESS PROCESS REENGINEERING (BPR) CONNECTION

Lean thinking is by no means a completely novel and unique concept. Two other approaches contain a number of the elements that Womack and Jones (1996) describe, namely: concurrent engineering and Business Process Reengineering. It is far from clear from the literature where the boundaries lie between the three. The terms used to describe BPR case studies sound remarkably similar to a lean thinking case studies, and when applied to the product development process, resemble the terms of reference for concurrent engineering. Perhaps this is not surprising when one considers the academic treatment of such techniques: numerous independent thinkers drawing off each other's work and definitions, but all trying to incorporate a new feature, slant or perspective, that develops current understanding. Under these circumstances it is unsurprising that there is considerable convergence between similar process improvement approaches.

When conducting the literature survey with the expressed intention of identifying the current application of lean thinking to construction, the author discovered that a considerable amount of *similar* work had been undertaken under the terms lean thinking, Business Process Reengineering and concurrent engineering. In elucidating the application of lean thinking to construction (section 2.4) the author has drawn from work using all three designations. It is for this reason that a brief treatment of BPR and concurrent engineering appear in this chapter.

2.3.1 Concurrent Engineering

Cleetus (1992) defines concurrent engineering as, *"a systematic approach to integrated and concurrent development of a product and its related processes, that emphasises response to customer expectations and embodies team values of co-operation, trust and sharing in such a manner that decision making proceeds with large intervals of parallel working by all life cycle perspectives early in the process, synchronised by comparatively brief exchanges to produce consensus."*

Anumba and Evbuomwan (1997) identify 9 goals for concurrent engineering. At least four of these are defined by Womack and Jones (1996) as essential to Lean Thinking:

- Proper analysis and establishment of customer requirements and specifications
- Location of multi-functional teams together when possible to facilitate better communications
- Continually focusing on improvement of the product and manufacturing process
- Reduction of product lead times and product costs

Broughton (1990) suggests that a particular aim of concurrent engineering is to improve quality and cost through the integration of design and manufacturing activities.

Love et al (1996) stress that down stream aspects of the total production process are affected by decisions made during the design phase. It is necessary to identify their impact on the final product as early as possible. Love et al (1996) go further by suggesting that the impact on down stream processes should be addressed using a multi-disciplinary team of experts. This approach should lead to a reduction in 'design rework' and a reduction in the product development lead time. Anumba and Evbuomwan (1997) also suggest the use of Design Function Deployment (DFD) as a means of capturing the client's requirements. DFD is a comprehensive design system based on QFD concepts.

This demonstrates a considerable overlap between the application of lean thinking to the product development process and concurrent engineering. Indeed some of the construction research papers use the terms interchangeably, for example Melhado (1998). It is far from clear where the boundary lies between the two concepts. Concurrent engineering does however stress the concept of 'concurrency' or performing activities in parallel, such as, functional design and consideration of manufacturing issues. Although not explicit in lean thinking, the use of co-located multi-disciplinary product development teams suggests that these issues are likely to be considered simultaneously. Another difference is that lean thinking suggests the use of *standardised work.* This concept is developed from production where procedures are created for each task. The work can then be thought of as 'standardised' and reduces the risk of quality variation between individual operators. Womack and Jones (1996) do not explain in great detail how this concept is applied to the product development process, although, it would seem to assume that there is a large degree of commonality between the product development processes for different products. This assumption may only hold for products within a particular family range, different cars or different buildings, for instance. Related to the idea of standardised work is the concept of 'flow'. Not only should there be procedures for the product development process within a lean environment, but work should 'flow' more easily from task to task. Again, it is not entirely clear how this is to be achieved, although, the ordering of tasks will be a critical issue. Another factor will be the removal of waste from the system in the form of information queuing, transfer and manipulation, and rework. Both approaches are strongly in favour of a multi-disciplinary product development team, co-located where possible. The 'voice of the customer' is also essential to both approaches as is the goal of reduced lead times. Lean thinking is however a far more comprehensive technique that seeks to improve the entire organisation through a few simple ideas, namely identifying and removing waste, specifying value and understanding how it is added to each product.

2.3.2 Business Process Reengineering (BPR)

A second relative to lean thinking is Business Process Reengineering. BPR has had wide coverage in the literature under such titles as 'Business Process Re-engineering', 'Process Reengineering' and 'Reengineering', the latter two titles alternatively spelt with a hyphen. For the purposes of this thesis the abbreviation BPR will be used, and where appropriate the spelling of 'reengineering' without a hyphen.

The originator of the concept claims the official definition of BPR is:

"The fundamental rethinking and radical redesign of business processes to bring about dramatic improvements in performance." (Hammer & Stanton, 1995)

The authors also indicate four key concepts within the definition.

1. *Dramatic*: reengineering seeks to make 'quantum leaps' in performance not just 5-10% increases. This is akin to the idea of kaikaku in lean thinking.

2. *Radical:* reengineering seeks to go to the root of what is trying to be achieved. It is not about tweaking existing processes but totally redesigning work methodologies utilising new technologies.

3. *Process:* a group of related tasks that together create value for a customer. The authors claim that the only way to achieve dramatic improvements is to consider processes holistically, i.e. need to overcome the often fragmented nature of a process within an organisation.

4. *Redesign:* reengineering is primarily about the design of how work is done. That is, redesigning an organisation's processes. This should lead to the elimination of work that is unnecessary and thus improve performance.

A key success factor in implementing reengineering is leadership from senior management. Given that sufficient backing is provided, the reengineering team has to work through four implementation stages:

1. Understanding the existing processes and customer requirements.

2. Invent a new process to replace the existing process.

3. Construct and test the new process.

4. Sell the new way of thinking to the organisation.

A three stage approach to implementing reengineering projects is common among consultants: (1) establish the scope of the project, (2) study the current process and (3) design the new process (O'Brien, 1995). Other approaches are suggested by Morris & Brandon (1994) and Obolensky (1996). Kettinger, Teng & Guha (1997) provide a comparison of methodologies. Regardless of the number of stages a reengineering project is broken down into, O'Brien (1995) suggests that four types of decisions are always taken:

1. *Scoping decisions:* which process(es) are to be reengineered.

2. *Design approach decisions:* decisions about how the design work is to be conducted, e.g. quantitative vs. qualitative methodologies, whether to simulate and at what level of detail processes should be mapped.

3. *Process design decisions:* any decisions which effect the design of a new process, e.g. choosing between different solutions, use of technologies, etc.

4. *Implementation approach decisions:* how to introduce the new process to the organisation to ensure successful adoption.

Lean thinking can be considered to be a subset of BPR with a specific underlying theoretical framework. In BPR it is necessary to identify customer requirements and understand existing processes. No particular tools or techniques are specified to achieve these goals. In lean thinking these objectives are accomplished by identifying 'value' and then mapping the 'value stream'. BPR does not have the specific philosophies of 'flow' and 'pull' as encountered in lean thinking, yet both concepts could be fully incorporated into a BPR project without compromising the integrity of the BPR approach. The notion of 'perfection' is included in lean thinking but not specified as a key ingredient of BPR. It is, however, difficult to believe that anybody in the change management industry subscribes to the view that the application of a BPR project will be a panacea but, rather, as technology changes, or insights into process organisation are gained, there will be a need to redesign work on an ad hoc basis. Thomson (1995) develops this idea into the concept of process monitoring for continuous improvement.

2.4 PROCESS IMPROVEMENT IN CONSTRUCTION

As was stated in section 2.3, lean thinking is not a unique technique but an approach that shares many features with other concepts, such as, concurrent engineering and BPR. Therefore, this section will largely draw upon the work of researchers involved in the application of lean thinking, BPR and concurrent engineering to construction. Other construction management research will be cited as appropriate.

Table 2.2 is an attempt at producing a 'loose' research map. The map is 'loose' because the research cited does not always fit into such neat categories, many of the papers could easily have been categorised under two (or more) headings. The map is by no means exhaustive, rather, it is representative of the researchers and the types of research which have recently been conducted under the process improvement banner. In table 2.2 the abbreviations in square brackets represent the terms of reference used by a particular author: [LT] – Lean thinking, [BPR] – Business Process Reengineering, [CE] – Concurrent Engineering, [Con] – Constructability and [BM] – Benchmarking. For the scope of this thesis the author is particularly interested in those researchers who identify their work within the lean thinking paradigm. The majority of work directly related to lean thinking in construction has focused on production and production planning. This is not reflected in the table, however, as numerous references were omitted as production is not the primary focus of the thesis. The design process category has a higher population than production, although, careful inspection will reveal that the majority of the papers do not use the lean thinking terms of reference. Instead, these papers relate to concurrent engineering and constructability.

Process	Concepts / Frameworks	Performance Measures	Applications	Tools
Design	Alarcón & Mardones (1998) [LT] Anumba et al (1997) [CE] Ballard & Koskela (1998) [LT] Bishop (1985) [Con] Chen et al (1996) [Con] Chen & McGeorge (1993/4) [Con] Construction Management Committee of the ASCE Construction Division (1991) [Con] Deasley & Lettice (1996) [CE] Evbuomwan & Anumba (1995) [CE] Formoso et al (1998) [LT] Hanlon & Sanvido (1995) [Con] Isatto & Formoso (1998) [LT] Melhado (1998) [LT] Moore (1996) [Con] O'Conner (1985) [Con]	Evans et al (1997) [Con] Tilley, et al (1997)	Houvila et al (1994) [LT, CE] O'Connor & Miller (1994) [Con, BM]	Alshawi & Underwood (1996) [Con] Amor & Clift (1997) [CE] Clift & Amor (1998) [CE] Glavinich (1995) [Con] Ho (1996) [BPR] Huovila et al (1994) [CE, LT] Huovila et al (1995) [LT] Huovila et al (2) (1995) [LT] Koskela et al (1997) [LT] Kaneta et al (1997) Lautanala (1995) Con] Luiten & Tolman (199?) [Con] Moore (1996) [Con] Moore & Tunnicliffe (1995) [Con] Patty et al (1995) [Con] Serpell & Wagner (1994) [LT] Turk et al (1997) [CE]
Procurement	Howell et al (1996) Miles & Ballard (1997) [LT]			Barlow (1996) [LT] Sidwell et al (1997) [BPR]

Process	Concepts / Frameworks	Performance Measures	Applications	Tools
Planning			Ballard (1997) [LT] Faniran et al (1997) [LT] Ghio (1997) [LT] Ghio et al (1997) [LT]	
Production	Koskela (1993) [LT] Melles (1994) [LT] Tommelein (1997) [LT]	Alarcón & Serpell (1996) [LT] O'Brien et al (1997) [LT]	Ballard et al (1997) [LT] Conte & Martinelli (1997) [LT] Fowler & Gray (1997) [LT] Fowler (1997) [LT] Kähkönen (1994) [LT] Tommelein (1997) [LT]	Atkin et al (1996) [BM] Fowler (1995) [BPR] Poh & Chen (1997) [Con] Russell et al (1994) [Con] Wang et al (1998) [Con]
Project Management		Howell & Ballard (1996) [LT]	Horman & Kenley (1996) [LT] Love et al (1997) [BPR] Love et al (1996) [BPR]	
Total Construction Process	Atkin (1998) [LT] Betts & Wood Harper (1994) [BPR] Love & Li (1998) [BPR] Love (1996) [BPR] Rogerson & Deasley (1996) [BPR] Serpell et al (1996) [LT]		Evans et al (1997) [BPR] Gibson et al (1996) [Con] Horman et al (1997) [LT] Ireland (1994) [BPR] Mohamed (1997) [BPR] Mohamed & Tucker (1996) [BPR]	Marosszeky & Karim (1997) [LT, BM]

Table 2.2 – Process Improvement Research in Construction

The application of lean thinking to the design process is not extensive and, therefore, this area serves as a suitable topic of study.

2.5 LEAN THINKING IN CONSTRUCTION DESIGN

Work by Lauri Koskela from VTT Finland was an important catalyst to the application of lean thinking to construction research. His first piece of work was written in 1992, and in 1993 he organised the first conference on lean construction (Alarcón, 1997). Since that time, numerous researchers have worked on the application of lean thinking to the production stage of the total construction process (Melles (1994), Tommelein (1997), Ballard & Howell (1994) and Fowler & Gray (1997)). Fewer researchers have tackled the applicability of lean thinking to design. Those that have can be divided into three groups: *conceptual foundations, methodologies / models* and *design tools / metrics.*

2.5.1 Conceptual Foundations

An important piece of work relating the theoretical foundations of lean thinking to construction design is Huovila et al (1994). This appears to be the first paper to try and identify the underlying issues of lean thinking and how they might be applied to the design process. The authors cite the traditional view of design as conversion, that is, requirements transformed into a design fulfilling those requirements. Huovila et al (1994) claim that this is a restrictive perspective which leads to inefficiencies. Design as *conversion, flow* and *value generation* is suggested as a superior model. Design as *conversion* relates to activities where requirements are transformed into design fulfilling those requirements. *Flow* is regarded as the flow of information to facilitate conversion activities and *value generation* is achieved through the fulfilment of requirements. At face value it would seem that conversion and value generation are one and the same, however, Huovila et al (1994) are trying to express that the actual activities being performed are conversion whilst the result of those activities is value generation. This is equivalent of Shingo's observation of the difference between operations and processes (Isatto & Formoso, 1998). The concepts provide two perspectives of the design process, that of the designer (operation) and that of the product (process). The designer performs activities which *convert* the 'ideas' into designs. The designs move from one stage of the process to another, say feasibility to scheme to detail, with *value* being *generated* as more and more requirements are fulfilled with an increasing level of design completed.

Within this framework, Huovila et al (1994) consider value generation to consist of two components: product performance and freedom from defects. The latter component can be equated with the quality of the design solution. If by 'product performance' the authors merely mean functional adequacy then their approach is somewhat deficient. If however 'product performance' has a much broader definition which includes cost / investment and timing attributes, as well as addressing stakeholder requirements other than the client, then this would be more acceptable. The authors go on to say that a way of identifying the value generated is by subtracting the value lost from 'best practice value or theoretically best practice value'. This would be tremendously difficult to achieve in practice as value is a moving target. However, this approach does focus the design team on aspects of the process where value can be lost, i.e. further waste identification. The authors cite four main possibilities for loss of value:

1. Part of requirements are missed at the outset.
2. Part of requirements are lost during design process.
3. There is too little improvement and optimisation of design solutions.
4. There are sheer errors in the final product design.

The corresponding solutions are said to be:

1. Rigorous requirements analysis at the outset in tight co-operation with the customer.
2. Systematised management of requirements, e.g. application of QFD.
3. Rapid iterations in major design issues to optimise design, use tools such as Taguchi methods, Design For Manufacture (DFM) and Design For Assembly (DFA).
4. Use of quality management to reduce waste.

Flow is an important concept in design as it suggests that some activities might actually be waste rather than an intrinsic part of conversion. A key element to lean thinking approach is to identify and remove waste from the process, Huovlia et al (1994) identify a number of waste types in the design process:

1. The inspection, storage and communication of information.
2. Not all requirements are captured at the beginning.
3. Rework due to errors, omissions and uncertainty - errors are detected in later phases leading to more costly rework.
4. Long or no iterations for improving design.
5. Waiting for approvals, instructions and information for the next step.

The major cause of rework in construction is uncertainty (Huovila et al, 1994). To reduce the amount of uncertainty in design the authors suggest five steps which can be taken:

1. The scope definition is done orderly to avoid scope changes.
2. All life cycle phases are considered simultaneously from conceptual stage to avoid iterations due to constraints in subsequent phases.
3. Prototyping and simulation can be used to decrease technological uncertainty.
4. In later stages of the project the design solution is practically frozen.
5. Design errors are reduced through quality management.

Other suggestions include co-locating the team to reduce the amount of effort required for information transfer and a reduction in the batch size of information transactions - the latter point can be addressed by decomposition of design tasks with intense informal communication and concurrency of work.

Ballard & Koskela (1998) state that the problem for design management research in construction is the 'lack of a solid conceptual foundation' which is compounded by the lack of empirical data. As such they suggest the adoption of Huovila et als' (1994) model: design as conversion, flow and value generation as a starting point. Given that the academic community embraces the theoretical framework, further work would be required to provide sufficient insights into the three components and their interrelationships. Isatto & Formoso (1998) warn of the problems of implementing ideas such as lean thinking without sufficient appreciation and understanding of the context in which the technique is to be applied. Indeed, the authors suggest that the principles of lean thinking may have to be specifically tailored to meet the needs of the industry. They posit a theoretical framework for design which suggests that, whatever approach is taken, in practice there is an order of precedence for particular aspects of design. This is outlined in figure 2.1. The difference between process and operation was outlined in this section in relation to the difference between conversion and value generation.

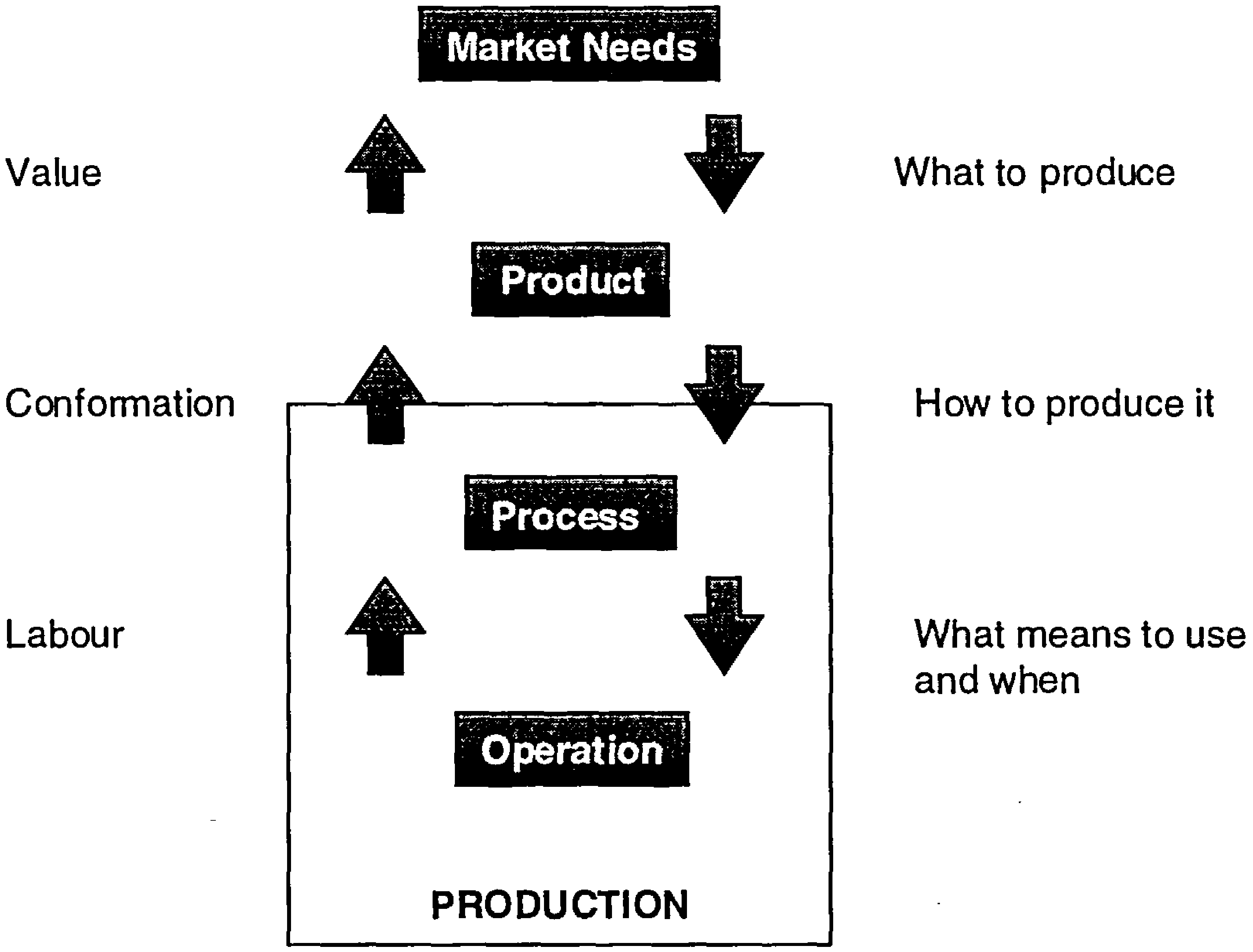


Figure 2.1 – Theoretical approach to design (Isatto & Formoso,1998)

2.5.2 Methodologies / Models

Models and methodologies for improving construction design, within the terms of reference of lean thinking, have been produced by Atkin (1998), Formoso et al (1998), Alarcón & Mardones (1998) and Melhado (1998). All of these models are developed at high level, comparable to the RIBA stages. Indeed, that which is proposed by Atkin (1998) is very similar in nature to the RIBA stages. An interesting addition to the model is that of 'advanced procurement' for systems with long lead times to help speed up the process. This stage is positioned between outline and detailed design. Atkin (1998) also suggests that the role of the quantity surveyor is not well integrated into the design process. The external quantity surveyor acts as a means of cost control rather than in a capacity of helping the design team to find solutions that provide better value for money. The author of this thesis agrees with this position. Atkin (1998) also suggests that managing client's requirements, integrating design and construction as a single process, value chain management and total project management are major factors in achieving project success.

Melhado (1998) suggests that product and production processes must be equally considered at the beginning of the design process. The author goes further by suggesting that design for production can be achieved by creating a new professional who deals with the development and detailing from the design for production perspective. This would be within the context of a multi-disciplinary team working within a concurrent engineering framework. Melhado (1998) also proposes that design co-ordination needs pre-established parameters and criteria in order to analyse design solutions properly. Another important feature is the concept of post-occupancy systematic evaluation as a means of providing feedback to the design team. This is essential for the design team, or individual professionals, if they are to improve with time.

Alarcón & Mardones (1998) suggest that there are several problems with traditional construction design. A particular problem lies in the lack of co-ordination between specialists and defects in the individual roles. This is compounded by changes during the project by both owner and designers. This can lead to inconsistencies among drawings and specifications. Another problem is that designers often lack construction knowledge which introdues problems at the construction stage such as loss of labour, idle times, rework, abnormal use of machinery / equipment and delays. Alarcón & Mardones (1998) have found that the most important design defects are lack of information and wrong information, with the most frequently occurring problem being continuous change / modification of the design. They conclude that the design process is chaotic and does not allow construction professionals complete exposure to the completed design and prevents iterations between different specialities. Alarcón & Mardones (1998) suggest a four stage solution to the problems outlined:

1. Supervision: include a construction company in the design process.
2. Improving co-ordination between specialities: through a logical sequence of information transfers. This is achieved through a planning scheme of the

design sequence for building projects to stabilise and control information flow. Also, implementation of a plan to control and evaluate changes during the execution stage.

3. Improving standardisation of design information: to verify that requirements of previous processes are fulfilled. Need to develop task lists to generate for each designer the input data for his own design process. Also, the development of work specifications in order to standardise the presentation of information and to establish requirements for different designers. There is a need to introduce construction criteria into the task lists and work specifications to reduce the impact of lack of construction knowledge.

4. Improve control: through development of check lists.

Formoso et al (1998) agree with Alarcón & Mardones (1998) that the design process needs to be planned and controlled more effectively in order to minimise the effects of complexity and uncertainty. Lack of design planning results in insufficient information being available to complete design tasks and inconsistencies within construction documents. As a means of improving construction design, Formoso et al (1998) suggest a design protocol consisting of a general plan of the design process which can be used as a basis for devising a model to manage the design process for individual companies. The main elements of the protocol are:

1. The content of the main activities.
2. Their precedence relationships.
3. The main inputs and outputs for each activity.
4. The tools that can be used to support the execution of each activity.
5. The roles and responsibilities of the different actors.
6. A model of information flow.

Formoso et al (1998) make an interesting point with regard to waste in the design process. That is, rework and design iteration should not be confused as iteration is an inherent and important part of the design process.

2.5.3 Design Tools / Metrics

Another area of research which has been conducted within the terms of reference of lean thinking is the application of tools and metrics. Three tools in particular have been studied: Quality Function Deployment (QFD), Design Structure Matrix (DSM) and Last Planner.

2.5.3.1 Quality Function Deployment (QFD)

QFD is a tool for capturing and managing customer requirements throughout the project. It was first proposed by Akao in the late 1960s as a means of 'capturing the voice of the customer' in the manufacturing context and translating it through the various stages of product planning, engineering and manufacturing into the final product (Moskowitz & Kim, 1997). The kernel of QFD is to capture and translate the needs of the customer into engineering characteristics and subsequently into parts' characteristics, process plans and production requirements associated with its manufacture. This is achieved by using a chart called the 'house of quality' (Moskowitz & Kim, 1997). Womack & Jones (1996) cite this as an important tool for lean product development.

Detailed descriptions of the tool can be found in Revelle et al (1998) and Cohen (1995). The application of QFD to construction has been considered by Huovila et al (1995(1)), Serpell & Wagner (1994) and Anumba & Evobuomwan (1996). Anumba & Evobuomwan (1996) suggest that QFD is an important tool for the construction industry and that it should be implemented within a concurrent engineering framework. Huovila et al (1995(1)) propose that applied to construction the tool is best suited to project managers as it provides them with a systematic means of compiling and understanding customer needs. From this, the most critical customer needs can be identified so that the corresponding physical properties can be focused upon. An additional feature of QFD is that it provides traceability within the decision making process.

The benefits of applying QFD include: shorter development time, smoother entry into production, features that appeal to customers, lower manufacturing costs and better quality (Clausing & Pugh, 1991). However, problems do exist with the implementation of the tool. A key issue is that customers do not always know what their needs are. Use of the tool means that customers are forced to consider and develop a better understanding of their requirements (Huovila et al, 1995(1)). This means that for the customer there is a large degree of satisfaction as his voice is systematically listened to with QFD. However, the tool can be quite laborious to use (Huovila et al, 1995(1)). Another issue that is relevant to construction is that the customer, or client, is often not the end user of the product. So even if the customer requirements are captured perfectly it would be the voice of the wrong customer that would be translated into physical attributes. This is a critical issue but one that is beyond the scope of the tool to solve, as in some cases the end users are not identified before construction is completed, e.g. tenants for office blocks or retail units. This problem will only be solved when lead times have been reduced sufficiently, such that, work can be delayed until an end user is identified.

2.5.3.2 Last Planner

The last planner is a tool that was originally designed to help stabilise work flow in the production phase. A detailed exposition of the tool can be found in (Ballard & Howell, 1994). The 'last planner' is the person who decides what production assignments are to be performed within the next time period. That is, actual production activities / operations rather than producing inputs for other planning exercises further down stream. The tool works on the basis of weekly work plans for production. The plans should ensure that:

1. Work is selected in the right sequence.
2. The right amount of work is selected.

3. The selected work can be achieved.

The tool utilises the principle of 'shielding' to protect the work force from upstream variations and uncertainty. This means for the purposes of the work plans it is very important to do work which can be undertaken / completed, for example, which is not subject to problems occurring in the supply chain within the period of that particular work plan. This requires a matching exercise between the labour force, work flow, resources, etc. The percentage of planned activities completed (PPC) is then calculated, i.e. matching what was achieved to the planned work. Non-completion of tasks is investigated to identify root causes. The use of the last planner produces a higher level of certainty and expectation for production teams. It promotes accountability, non-production time falls and process control is improved.

Applying this approach to planning and work execution to the design process is discussed by Koskela et al (1997). The authors suggest that the sequencing of design tasks for the work plan can be achieved by Design Structure Matrix (DSM), although they rightly point out that this tool is sill in the research stage (a discussion about this tool can be found in section 2.5.3.3). This should be done in conjunction with the pooled experience of the entire design team. The aim is to try to optimise the order of tasks based on interdependencies of individual operations. However, even if the optimum order of tasks is more or less known, problems can still occur due to the high level of associated uncertainty and half-heartedness of effort to control the design process (Koskela et al, 1997).

For the purposes of their case study the authors (Koskela et al, 1997) used DSM and the experience of the design team through a series of interviews to establish a monthly work plan / schedule. The schedule was updated regularly rather than introducing more detail. Information needs reported by designers in design meetings were recorded. Tasks for the next period (taken from schedule) and information needs were agreed and attached as 'assigned design tasks' in the minutes. All design team members received a copy of the minutes immediately after the meeting, thus, each role was presented with a form detailing his / her scheduled design work for the period. In the next meeting the assigned tasks were systematically dealt with and monitored. The assigned task forms were returned by all parties along with information about the realisation of each task and causes for non-realisation. Progress, as measured by considering actual work against planned work, was not discussed in the meetings to prevent an atmosphere of overly tight control (Koskela et al, 1997). An interesting omission from the paper is the break down of task realisation on the basis of each party. This is a very sensitive issue of course and in practice could lead to a massaging of the figures to save face. Rightly or wrongly, such figures could also be used in the selection of companies / individuals who score highly in this particular metric.

The main causes for lack of task realisation are 'had no time due to other tasks' ~ 40% and 'lacking input information' ~ 30%. The former is largely a resource allocation issue whilst the latter could be a reflection on the sequencing of work and / or failure of other parties to complete their tasks on time. A result of applying the last planner tool in this fashion was a 30% saving in design time. A second advantage was the transparency achieved by using a design schedule which means that the impact of a design change can be better analysed in advance. The PPC graphs can show the effects of erratic decision making by the client and can also be used as a benchmark to set targets for, and monitor, project progress. With regard to lean thinking, however, this tool does not seek to standardise the approach to construction design as it operates at the task level. It does offer an improved design plan which can lead to better design control for a particular project, but further benefits can be gained by seeking a means of standardising the approach to product development (Womack & Jones, 1996).

2.5.3.3 Design Structure Matrix (DSM) / Analytical Design Planning Technique (ADePT)

The Design Structure Matrix (DSM) was developed by Steward in the early 1980s. It is a tool that can be used to assess the interdependencies between tasks in a process. It does not tell how or why individual operations effect each other but simply that they do (Huovila et al, 1995(2)). The knowledge can be used to try to optimise the particular process. The matrix indicates which tasks must be completed in series and those in parallel. An advantage of this tool is that it can cope with the iterative nature of design. Data regarding the interaction of tasks / sub-processes is entered into the precedence matrix. A partitioning algorithm is used which moves elements within the matrix below the diagonal or into square blocks about the diagonal. If there are no circuits all the elements will be below the diagonal. The block is the smallest possible such that all the variables that occur in the cycle will be found in the same block. The tasks within a block are coupled and, therefore, have to be done jointly (in parallel). The matrix indicates the right order in which tasks should be performed, whether sequentially or in parallel. It also shows the information dependencies between tasks.

The application of DSM to construction has been considered by Huovila et al (1995(2)) and Koskela et al (1997) – as part of the implementation of the 'last planner' method (see section 2.5.3.2). Huovila et al (1995(2)) found that the tool can be used effectively in construction to find better sequences for design tasks, however, if used manually, is very laborious. They envisage that the tool will be used for the planning and management of design, for fast tracking analysis (sequencing for speed of design) and analysing the potential effects of design change. This latter point is increasingly a concern for design practitioners.

DSM has also been considered by Austin et al (1999) within the context of developing a design management tool - 'Analytical Design Planning Technique' (ADePT). DSM is an important component of ADePT. The fist stage of the research is to establish a process model that graphically maps the detailed design tasks in construction design, and the information that flows between them. The maps also identify the role that each of the disciplines undertakes (this will no doubt be dependent upon the contractual agreement for each project). The map is analysed using DSM to optimise the order of design tasks. From the results of the matrix analysis design schedules and programmes can be constructed (Austin et al, 1998). An interesting addition to the DSM methodology is the classification of information, so not only are the information inputs identified, they are also rated as to how critical the information requirement is on a six point scale (A – most critical to C – least critical. Also uses A/B, B/C and A-C) (Austin et al, 1998). This provides an additional dimension to the ordering of design tasks to provide the optimum sequence.

2.5.3.4 Metrics

Two areas for producing useful metrics are suggested by Tilley et al (1997), namely, Requests For Information (RFIs) and the drawing registry. Analysing the number of individual contract drawings issued and the number of revisions made to those drawings allows a comparison between projects and the design disciplines involved. This provides an overall impression of design documentation deficiency. An analysis of the RFI process provides a better indicator of the overall quality of the design documentation process. Analysing the volume of RFIs in relation to contract value and project duration provides an indication of the extent of design documentation deficiencies [1], whilst an assessment of there response times provides an indication of their severity [2] (Tilley et al 1997).

In relation to RFIs, two performance indicators are suggested to facilitate calculation of design documentation deficiency at the project level:

$$PI_1 = \frac{N_c}{CV \times D} \qquad [1]$$

Where:

PI_1 – Performance Indicator 1
N_c – Number of *information clarification* type RFIs
CV – Estimated final contract value
D – Initial project duration

$$PI_2 = \frac{1}{N_c} \sum \frac{T_a - T_r}{T_a} \qquad [2]$$

Where:

PI_2 – Performance Indicator 2
N_c – Number of information clarification type RFIs
T_a – Actual time of response
T_r – Response time required

Condition: If $T_r \geq T_a$ then $(T_a - T_r) = 0$

This mathematical constraint, or condition, is provided to eliminate the counter-acting effect that within-time responses would have upon the value of the *beyond-time* performance indicator (Tiley et al (1997).

Another metric is the percentage of planned activities completed (PPC) as used in the last planner method (Koskela et al, 1997) (see section 2.5.3.2).

Other metrics include those developed by the Construction Best Practice Programme, in the UK. These are a series of measures that allow companies to benchmark themselves against objective data to assess their company's performance. They include measures on:

- Client satisfaction – product
- Client satisfaction – service
- Number of defects
- Predictability – cost
- Predictability – time
- Profitability
- Productivity
- Safety
- Construction cost
- Construction time

Interestingly, there appears to be a lack of metrics available to assess progress within individual processes, with the exception of the RFI performance indicators, but even these are after the event as far as design is concerned. The above metrics operate at the project level, which essentially are output measurements. They may be useful for companies to benchmark themselves against one another but they do not effect the outcome of the project that has been benchmarked. It would be desirable to have a set of metrics that the design team can respond to during a particular project to ensure the quality and speedy delivery of the product being designed.

2.6 CONCLUSIONS

The lean thinking paradigm suggests a five step change management approach that can make organisations lean:

1. Understanding what the client *values.*
2. Identify and remove waste within the organisation by analysing the *value stream.*
3. Facilitate value *flow* through the organisation.
4. Value should be *pulled* through the processes, initiated by the client.
5. Continuous improvement – *strive for perfection.*

Five factors have also been identified that directly relate the lean philosophy to the product development process:

i. Single leader responsible for the product.
ii. Multidisciplinary teams, co-located where possible.
iii. Clearly defined responsibilities for all team disciplines.
iv. Standardised approach to product development.
v. Ensure that the voice of the customer is heard throughout the product development process.

The five factors above are key issues for making construction design lean and should be considered in conjunction with the five step change management approach. Although 'ensuring that the voice of the customer is heard throughout the product development process' could be considered to be the most important factor in the design process, this issue has been considered in some depth through QFD research. Another issue of significant importance which has received little attention is that of a standardised approach to product development. A standardised approach is adopted to help improve control of the process, such that, the design team can benefit from the learning curve of repeating the same product development process for each new product. The other three factors (single leader responsible for the product, multidisciplinary teams, co-located where possible, clearly defined responsibilities for all team disciplines) should in theory be achievable for those who are willing to accept organisational changes and invest the time an effort to clarify individual roles. One issue that is perhaps peculiar to construction due to the fragmentation of the industry, is the difficulty in, or perhaps the resistance to, co-locating design teams. This is in part due to the fact that designers are often working on more than one project whilst based within their own organisation and would therefore create a major resource issue, especially for smaller companies. There is no obvious solution to the problem as construction projects are by their nature site based which could mean a significant amount of travel involved for the personnel concerned. Perhaps information technologies could play a key role here through the electronic sharing of information, video conferencing, etc.

The application of lean thinking to construction has largely concentrated on production planning and production phases of construction projects, however, some work has been undertaken with the application of lean thinking to construction design. This work has been split into three main categories:

1. Conceptual foundations.
2. Methodologies / models.
3. Design tools / metrics.

With regard to conceptual foundations, the view of design as conversion, flow and value generation is an important step for the industry to realise that waste does exist within the design process and needs to be addressed. This view, perhaps for the first time in construction, will emphasise the 'process' in the term design process. This view of design also helps to underpin the idea of the design decision maps as value generation maps in chapter 7 of this thesis. In the methodologies /

models section of the literature survey a number of the lean thinking factors have been incorporated into the approaches outlined. However, there appears to be a lack of empirical data to suggest improvements that these models / methodologies have led to. One issue that arose was the lack of sufficient design planning on construction projects which leads to greater uncertainty and less effective control of the design process. Two design tools have been used to address this problem: last planner and the ADePT methodology. The last planner method was originally developed for the production phase of projects and was adapted to be used in construction design. It operates at the task level by producing monthly work plans. The ADePT tool was developed to plan and optimise design, planning at the detailed design level using DSM. Related to the lack of design planning is the lack of a standardised approach to the product development process. Although models of the design process seek to address this issue they are often at a level of abstraction that is too high to have a significant impact. Appropriate design planning tools might actually lead to a more standardised approach. To achieve this it is the opinion of the author that it might be more appropriate that they operate at the value generation level rather than the task level. Value generation is equivalent to design decisions in construction design. When making a decision on the basis of considering and testing design constraints and options a number of tasks have to be performed. To make any particular decision a number of different sets of tasks may be performed, or the same set of tasks in a different order, with differing amounts of effort. For instance, a survey may or may not be conducted, a variety of drawings may or may not be produced. Also, depending upon previous decisions made, choosing between brick or a cladding system for the external skin, for example, will require a different set of tasks to perform more detailed design. However, if planning takes place at the decision level, regardless of how the decision is reached, the decision still has to be made within the project constraints. Therefore to standardise at the task level is more problematic than standardising at the decision level.

The second part of the literature survey, construction design, is documented in chapter 3.

[BLANK PAGE]

CHAPTER 3 THE CREATIVITY ENIGMA: DESIGN IN CONSTRUCTION

Literature Survey: Part 2

> *"Now what is the process of design? The process of design is analyse, analyse, analyse, analyse. Analyse the site, analyse the problem, analyse the line of the existing bridge, analyse the nature of the geology there, the nature of the landscape there, analyse the political views of people, analyse who lives where. The trick is not to commit to any idea. It's actually to analyse...keep on analysing the problem...just keep on analysing the problem and deliberately staying off a solution and not committing to a solution until one has gathered enough information, then you find the designs just kind of take care of themselves."* **Tim Quick, Sir Norman Foster and Partners.**

CHAPTER 3 THE CREATIVITY ENIGMA: DESIGN IN CONSTRUCTION.................37
3.1 INTRODUCTION..38
3.2 PSCHOLOGYICAL & SOCIOLOGICAL PERSPECTIVES OF DESIGN.............43
3.3 MACRO DESIGN MODELS..47
3.4 AXIOMATIC DESIGN..52
3.5 DESIGN FOR MANUFACTURE (DFM) / DESIGN FOR ASSEMBLY (DFA)......54
3.6 CONSTRUCTION DESIGN METHODS / APPROACHES.................54
3.7 CONSLUSIONS..58

3.1 INTRODUCTION

This chapter deals with the different aspects of design research that have been undertaken. It largely draws on work conducted in the field of construction design, although not exclusively, as some of the ideas developed in the manufacturing sector and mechanical / electrical design, show considerable commonality with, and potential for, construction design.

Design has various meanings ranging from purposive planning to plotting with evil intent and, in any case, evokes notions of rationality and carefully conceived effectiveness (Anderson, 1984). Added to such a logical approach is the phenomenon of serendipity, or the 'eureka', factor which seems to push the activity of design towards the mysterious. The word design is used in numerous fields from artistic to industrial and as a noun relates to the form / nature of products as diverse as fabrics and microprocessors. It can be considered to be a vague term but, as a verb, can be thought of as relating to the continuous interplay between what we want to achieve and how we want to achieve it (Suh, 1990). Carrara, Kalay & Novembri (1992) provide a more specific definition for a particular context, namely architectural design: 'an extremely complex set of operations aimed at the definition of a built object that achieves a predefined set of required performances', and comprises of three main operations:

1. Defining a set of required functional characteristics that comprise the objectives to be achieved by the designed artefact.
2. Making design decisions that in the opinion of the designer are (or should) be capable of achieving the predetermined objectives.
3. Verifying that these choices are internally consistent and that they achieve the required functional characteristics.

This particular view of design is important within the context of this thesis as this chapter strives to elucidate the key issues relating to design in the construction context. Understanding the architectural component is obviously an important issue in the drive to make construction design lean. For the purposes of this thesis, the design process is considered to be all the decisions made, and tasks performed, to articulate the building's characteristics in an unambiguous fashion. That is, from inception to the start of construction, with particular emphasis on system level decisions. To help provide an overview of some of the research that has been conducted into design and design process improvement, a loose research map has been produced and is presented in table 3.1. The map is 'loose' because the research cited does not always fit into such neat categories, many of the papers could easily have been categorised under two (or more) headings. The map is by no means exhaustive, rather it is representative of the researchers and the types of research which have been conducted into design. In table 3.1 the abbreviations in square brackets represent the terms of reference used by a particular author: [BPR] – Business Process Reengineering, [Con] – Constructability, [BM] – Benchmarking [QFD] – Quality Function Deployment, [DFM] – Design for Manufacture, [DFA] – Design for Assembly, [AD] – Axiomatic Design and [TQM] – Total Quality Management (where applicable).

Process	Models / Concepts	Investigative	Approaches / Techniques	Applications	Tools
Design Planning					Austin et al (1999) Austin et al (1998) Austin, Baldwin & Newton (1996)
Requirements Capture / Briefing	Garaza & Alcantara (1995)		Blyth (1995)	Atkin et al (1996) [BM] Barret (1999) Bowen et al (1997) Cairns (1996) National Economic Development Office (1974) O'Reilly (1973) Smith et al (1998)	Anumba et al (1996) [QFD] Franceschini & Rossetto (1995) [QFD] Huovila & Serén (1995) [QFD]
Concept Design	Koppelaar (1991) Schmitt (1992) Tovey (1991)		Otto (1995)		Hacfoort & Veldhuisen (1992) Hennessey (1994) Mahdavi & Suter (1998) Moore & Miles (1996) Naoum & Fong (1995) Pollalis (1994) Tang (1995) Wrona & Olszynski (1985)

Process	Models / Concepts	Investigative	Approaches / Techniques	Applications	Tools
Detailed Design					Boothroyd (1994) [DFM, DFA] Leaney & Wittenberg (1992) [DFM, DFA]
Total Design Process / Design in General	Alarcón, Ashley & Teicholz (1997) Eastman & Fereshetian (1994) Goldschmidt (1992) Hazlehurst (1995) Johnson (1992) Kalay et al (1998) Li & Love (1999) Oakland & Oakland (1997) RIBA (1992) Sanvido (1990) Sheath et al (1998) Whitney (1990)	Ball, Maskill & Ormerod (1998) Christiaans & Venselaar (1991) Coles (1990) Fazio & Bédard (1992) Frankenberger & Badke-Schaub (1998) Walsh & Roy (1985)	Alarcón et al (1997) Gray, Hughes & Bennett (1994) Krouwel (1991) McGeorge & Palmer (1997) [VE /BPR/ Con/TQM/ BM] Sekine & Arai (1994) Suh (1990) [AD]		Alshawi (1995) Augenbroe (1994) Fenves et al (1992) Kalay (1992) Liggett, Mitchell & Tan (1992) Manning & Mattar (1992) McGeorge et al (1995) Moore & Miles (1995) Vanegas & Nguyen (1997) Wiezel & Becker (1992)

Process	Models / Concepts	Investigative	Approaches / Techniques	Applications	Tools
Psychological / Sociological Perspectives of Design	Akin & Akin (1998) Baya & Leifer (1994) Carrara, Kalay & Novembri (1992) Demirkan (1998) Hamel (1994) Gross (1984) Madanshetty (1995) Mitchell (1992) Roozenberg (1991) Valkenburg (1998) Wallace (1991)	Akin (1991) Anderson (1984) Chan (1990) Cross (1991) Ehrlenspiel & Dylla (1993) Goldschmidt (1991) Goldshmidt (1990) Gross & Fleisher (1984) Lloyd & Deasley (1998) Lloyd & Scott (1994) Mazijoglou & Scrivener (1998) Minneman & Leifer (1993) Schön (1984) Visser (1993)	Goel & Pirolli (1989)		Cross (1985)

Table 3.1 – Research into Design

[BLANK PAGE]

3.2 PSCHOLOGYICAL & SOCIOLOGICAL PERSPECTIVES OF DESIGN

3.2.1 Introduction

A lot of work has been conducted regarding the psychological and sociological perspectives of design. The psychological investigations seek to establish 'how' individual designers design. What cognitive processes take place that lead a person to a particular design solution. Indeed, the key questions are what is creativity and how can we become more creative? How can we produce more innovative design? Is there a mechanism which can be learnt or is 'good' design an innate ability which is the preserve of the talented few? Part of the debate, which to some extent represents the limits of knowledge, is the contention between the rational and the irrational, or the serendipitous vs. the systematic nature of design. The subject became a serious area of research in the late sixties and early seventies when Eastman performed the first protocol analysis of architectural design. The approach was to identify the operational aspects of the cognitive system and to describe tasks within a general taxonomy of tasks within the 'information processing theory' paradigm (Akin, 1991). In the research that followed over the next thirty years or so, the favoured approaches to elucidate the issues involved in design included interviews with designers, observations and case studies, protocol studies, controlled tests, simulation trials and reflecting and theorising (Cross, 1991). As well as categorising research by the methodologies adopted it is also possible to consider the refinement of the research questions, or aspects of design that were emphasised by various scholars. That is not to say that design itself was dissected into smaller more manageable chunks but rather different perspectives of design fundamentals were explored. Alternative perspectives included, the internal and external representations of designed objects, the knowledge base of design thinking, the formulation of design problems, the thought processes that apply to design learning, refining the general descriptions of the design processes offered by the ground work in design research, prescriptive accounts of the design process and design methods (Akin, 1991). However, despite these seemingly neat and distinct categories, Akin offers the caveat that there is a lack of clarity about the subject matter in much design research and often the purpose of the study, and the interpretation of the results, can be unclear. The author of this thesis is sympathetic to this view because of the difficulty experienced when trying to structure the material for the purposes of this chapter.

The sociological perspective of design considers how the interaction of two or more designers effects problem solving and creativity. It also seeks to address whether anything can be done to enhance that interaction to improve the quality of design output. This is a particularly important aspect of design research as the vast majority of industrial design is performed by design teams. Design teams are made up of a number of people, often with different areas of expertise. It is inescapable that at some stage these designers have to work alone on particular tasks, however, the key to design teams, or teams of any kind, is that the synergy created between individuals is such that the whole is greater than the sum of their individual efforts.

Both of these perspectives of design have been considered across a variety of design disciplines including, mechanical engineering, electrical engineering and architectural design.

3.2.2 Design Models

A fair question to ask of design researchers is, 'why bother creating models of the design process, based on what people already do?' Establishing a design model, or method, is akin to the idea of best practice. It is thought that by codifying the way in which good designers work into a model, or methodology, it is possible to emulate them. The idea being that following a model, like a recipe, will lead to consistently good results. Interestingly, this notion is resonant of the concept of standardised work within the lean thinking paradigm. Whilst this approach provides useful insights into the type of activities that designers perform on route to a design solution, it does not provide any insights into the nature of inspiration – the eureka factor. It might not be possible to teach serendipity, however, the generation of models may help equip designers with the right approach and tools to improve the likelihood, or indeed facilitate, flashes of inspiration. Essentially, models of design with respect to the individual designer take two forms: what designers do, and how they do it. In terms of how design is achieved, this usually refers to modes of thinking. That is, how a designer moves from a specified problem or design situation to the final solution. It would seem to be commonly held that designers display essentially three modes of thought: deductive, inductive and abductive (Demirkin, 1998 and Roozenburg, 1991). Deduction is reasoning from the general to the to the particular, induction - from a set of given examples the rule is identified, and abduction is the derivation of statements about the world given logical rules and some logical consequences (Demirkin, 1998). Roozenburg (1991) goes on to state that the key mode of design reasoning is abduction. Models of what designers do include Hamel's (1994) view of architectural design as that of gathering information, decomposing the problem, solving partial problems, synthesising partial solutions and moulding the results into a design. Hamel (1994) also states that all sub-problems are tackled in the same sequential manner. Demirkin (1998) presents a model of design as identifying and interpreting the problem to create a conceptual model. This conceptual model is then translated into a design model, which is implemented to produce the artefact. The author goes on to explain how the conceptual model is produced from the designer's knowledge base by rule and case based type reasoning. It presupposes design solutions in the designer's memory and therefore implies a degree of domain or specific problem experience / knowledge. The rule based thinking can be considered to be equivalent of testing constraints and, as such, can be equated to Chan's (1990) 'selecting of constraint schema' (see section 3.2.3).

Engineering models of design are based on analysis proceeding the synthesis of solutions, where as architectural models are based around the idea that solution concepts precede problem analysis. In other words, architects need to generate a solution before they can think about the problem. Computer programming models describe designers negotiating the structure of design problem; either in opportunistic ways, regular ways or a combination of the two (Lloyd & Scott, 1994). However, the authors found that designers (five electrical engineers) display characteristics of all three models whilst designing and that the strongest determinant of the approach that a designer takes is whether the designer has had experience of the specific problem type. When they have experience of the particular problem type, designers approach design tasks through solutions rather than through problems. This is a very important factor, as knowledge / experience of the specific area has been found to be far more important then general knowledge of the field.

3.2.3 Protocol Analysis

Protocol analysis is a technique that attempts to 'eavesdrop' on the design process by asking designers to think aloud whilst working on a design problem. These commentaries are recorded using either video or audio equipment. The former of the two provides a richer picture as it also captures the development of solutions, designer's movements, etc. The technique is very much concerned with identifying how designers think, moving from the stated objectives of the exercise through to the final solution produced. A criticism levelled at this technique is that designers do not normally verbalise what they are thinking and that investigating design from this perspective might actually produce a distorted picture of their cognitive processes – observation effects the measurement, factor. Another issue that arises is that design work is often carried out in laboratory like experiments and not the normal working environment. However, despite these drawbacks, protocol analysis is really the only technique that provides insights into the cogitative processes of designers. Other methods tend to be restricted to assessing the design output (sketches, notes, final solution, calculations, etc.) and making inferences about cognition, from them.

Numerous protocol studies have been published in the literature. These involve a variety of researchers with different research agendas. For example, Lloyd & Scott (1994) hypothesised that regardless of the designer's field, designers would use similar cogitative approaches to solve problems. The authors found that it is the designer's experience that plays a pivotal role in determining the design process. Baya & Leifer (1994) use protocol analysis to investigate the information handling ability of designers in the concept stage. They suggest that there is proportionality between the time spent on design and the amount of information handled, although the authors recognise that they used a very small sample size and that there work is far from conclusive. Ehrlenspiel & Dylla (1993) attempt to identify what characterises a good designer. The authors propose that if the findings can be confirmed a general design methodology can be produced. They suggest that successful designers are / do:

1. More precise when they analyse and formulate requirements and they spend more time doing it.
2. Spend more time searching for solutions.
3. They are able to apply a goal-directed abstraction – prioritise from most to least important.

4. They are not satisfied with the first single sub-solution.
5. They evaluate solutions more accurately and spend a larger amount of time on this.
6. They work their way through problems according to major functions.
7. They have better spatial imagination.
8. They apply meaningful strategies for steering the design process.

This compares with Chan's (1990) findings that the ability of a designer is determined by 'the ability of selecting rules in constraint schema'. That is, the designers ability to prioritise constraints and produce additional constraints / rules to find a solution when one cannot be found within the constraints already identified. Related to this is the ability to 'generate new constraints for testing a newly generated design unit'. When a design solution has been produced for a particular aspect of the total design it needs to be evaluated against some criteria, or constraints. It is the ability to identify new constraints that are generated by the solution on the rest of the scheme that Chan (1990) states is a key determinant of the ability of the designer. Goldschmidt (1990) uses protocol analysis to establish a measure of a designer's productivity. The design process, according to Goldschmidt, is made up of a succession of acts of reasoning, or design moves. On the basis of the protocol data, Goldschmidt investigated the links between design moves produced by designers and produced an index value for each participant in the experiment. It was found that a systematic correlation exists between the link index values and the state of the emerging design entity in terms of its comprehensiveness and coherence. In other words, good designers make lots of links between individual acts of reasoning and perform them in a structured manner. This is very interesting from an academic perspective, however, the lessons to be learnt are somewhat limited even when related back to the production of design models / methods and the idea of best practice. The difficulty lies in what is an innate ability, or talent, and what can be taught, encouraged and copied. Is it possible to teach somebody to make more links between their acts of reasoning or will this always be a function of intellegence? Perhaps the issue of knowledge / experience of specific design problems is a factor, the more experienced the greater the ability to make links? The same criticism can be levelled at Ehrlenspiel & Dylla (1993) when they talk about producing a general model on the basis of their findings. How is it possible to incorporate the fact that good designers have better spatial awareness into a general design model? Again, can better spatial awareness be taught, or is this a function of a persons intelligence? If it can be taught, perhaps a series of exercises should be devised that designers can perform to flex their intellectual muscle, as athletes do to the body.

3.2.4 Sociological Perspective

The sociological perspective of design is a necessary insight in an industrial context, as design is rarely performed in isolation. Indeed, design often consists of numerous individuals with different educational backgrounds, disciplines, specific knowledge and skills. To some extent this is considered indirectly through the development of approaches to design such as lean thinking, where the design of the design process is considered in some detail, such as the use of co-located multifunctional teams. This type of research differs from design approaches, in that, it is the study of designers in the design context, i.e. what designers do rather that what designer's should do. The aim of sociological research is to improve the interaction of design team members to produce better design solutions in a more efficient manner. This is achieved through observing how designers interact and making inferences form the observations.

From this approach, design can be considered to be a process of attempting to achieve a shared understanding between the participants with the aim of communicating knowledge and ideas to produce better design solutions (Valkenburg, 1998). It is this shared understanding, or process of communicating, that is crucial for successful team design, as designers from different design disciplines often use taxonomies peculiar to their own fields. Both Visser (1993) and Lloyd & Deasley (1998) consider negotiation to be an important component of the social interactions within design. Visser (1993) views negotiation to be critical when choosing between design options. Issues such as perceptions of expertise, authority (seniority) or the ability to argue competently are very influential when selecting a particular option over another. Frankenberger & Badke-Schaub (1998) have found that not only is experience an important factor when choosing between design options but also the relationship of experience to hierarchical power. That is, experience is only useful if somebody with greater seniority does not over rule a less senior but more experienced person. Lloyd & Deasley (1998) agree with Valkenburg (1998) that design teams attempt to establish a common understanding of the design problem and use negotiation as a means of achieving consensus. Lloyd & Deasley (1998) also found that unofficial organisation was a highly effective means of progressing work and that a key component of progress is the need for trust relationships, both official and unofficial. The authors also noted that less than 30% of time was given over to the design action, or concentrated design work.

3.3 MACRO DESIGN MODELS

Macro design models outline the total design process, representing the sorts of activities and the order in which they should be performed and, as such, tend to be highly systematic. They are high level models that conceptually sit above the real design process but are a useful means of breaking a complex set of tasks into manageable phases. They differ from models of individual designers in that they consider the process from the product's point of view in the stages that are required to produce a particular article. This statement requires qualification, however, as the models may contain certain biases towards disciplines, procurement routes and particular parts of the total process. They tend to suggest a gradual movement from the general to the specific, simple to sophisticated, and schema to detail. Essentially, there is general agreement on the form of systematic models (Wallace, 1991). However, in construction projects the reality can be quite different with various building attributes, or components, at different stages of development, i.e. designed with a greater level of detail than others. Some models indicate the types of activities that should be undertaken within particular design phases (e.g. RIBA, 1992) and some even go as far as suggesting tools and resources that can be used (e.g. Kagioglou, 1998). Sanvido (1990) uses $IDEF_0$ to map the design process and found that design in construction consists of understanding functional requirements, exploring concepts, developing systems schematics, detailing designs (the author uses the term 'developing design' but explains it as detailing), communicating the design to others and maintaining design information and models. This is consistent with the generality of systematic design models outlined by Wallace (1991). The modelling goes on to identify the main tasks associated with each of these design stages. Baldwin et al (1999) take the view that existing models of the building process are inadequate for the purposes of understanding information related events such as planning and scheduling design tasks, as they do not address information interdependencies of design activities and the necessary information flow. This is perhaps unsurprising as most models do not seek to address these issues but rather provide a framework which both describes design activity and can be used as a guide to design organisation. As a result, the authors have produced a generic data flow model for the conceptual and schematic design stages - this is related to their work on DSM (see section 2.5.3.3). Such a step goes beyond the current usage of models in construction design which is largely due to the trend of the application of process improvement thinking. It also means that an order of magnitude of greater detail is required for modelling purposes.

To complete this section, special attention will be given to three macro design models: RIBA, BAA and Process Protocol. The first because it is widely used within the construction industry and the others because they represent recent thought on the development of process models in construction and have been influenced by product development models from the manufacturing sector. Also, the BAA model was used in one of the case studies in chapter 7.

3.3.1 RIBA

The Royal Institute of British Architects (RIBA) (1992) Standard Form of Agreement for the Appointment of an Architect provides a commonly used model for structuring construction projects. The model is high level and offers guidance as to when the client should expect, and pay for, particular activities in a highly complex process. The model is linear and proposes a number of sequential stages which funnel a large number of basic concepts to a low number (ultimately 1) of detailed designs. Within each stage several activities are performed some of which may be done in parallel. Essentially this model is quite abstract when compared to the reality of a construction project. Often different aspects of the design are at different RIBA stages by virtue of the amount of detail that has been generated, and because of clients with ambitious programmes, some stages are actually run in parallel, gambling on a sympathetic planning authority, for instance. However, the model is still useful as a guide and conceptually 'sits above' the real activity. The main stages are shown below.

Stage	Description
A – B	Inception and Feasibility

C	Outline Proposals
D	Scheme Design
E	Detail Design
F – G	Production Information and Bills of Quantities
H	Tender Action
J	Project Planning
K – L	Operations on Site and Completion

A key issue for industry when using this type of model is to what extent does such a model actually seek to control the process. In the case of the RIBA model, the answer is very little. As stated, the model was conceived to facilitate the timely and fair payment of architectural services. It is also useful from a client's perspective, as he is able to gauge whether the architect is performing the correct types of activities at any particular time. However, the transition from one phase to another in reality may be ill defined, and in some cases, undetectable. Indeed, Baldwin et al (1999), describe the boundaries between phases as 'fuzzy'. Proceeding to the next design phase is not dependent upon completion of the previous phase. Therefore, the RIBA model can be thought of applying structure to the design process through contractual expediency rather than the active control which is desirable from a process management perspective. This particular model also incorporates an underlying procurement route philosophy, namely competitive tender. When compared with Sanvido's (1990) design model a large degree of similarity is found to exist. Sanvido's (1990) model extends beyond design and indeed incorporates other aspects of the total construction process, such as facility management, which are not contained in the RIBA model. But with regard to the design process, the subject of this enquiry, the commonality is immediately obvious.

3.3.2 BAA

A recent guide to the construction project process issued by the British Airports Authority (BAA) set out the following framework:

Stage	**Description**
A	Inception
B	Feasibility
C	Concept Design
D	Co-ordinated Design
E	Production Information
F	Construction
G	Operation & Maintenance

Project Activities

1. Development Management
2. Evaluation and Approval
3. Design Management
4. Cost Management
5. Procurement Management
6. Health and Safety
7. Implementation and Control
8. Commission and Handover

Inception is de-coupled from feasibility in this instance which reflects BAA's internal decision making process. All construction projects on BAA's airports are planned well in advance of actual implementation through the BAA master plan. This is the company's long range planning strategy based on forecasts of future needs for facilities and, as such, reflects the fact that BAA is a construction client. Another difference from the RIBA model is that the three RIBA design stages 'outline', 'scheme' and 'detail' have been compressed into two: 'concept' and 'co-ordinated' design. Also, there is the omission of a tender stage as BAA operates a partnering framework with a number of suppliers and design consultants. This again suggests that these models have an assumed underlying procurement route philosophy. The BAA model also seeks to exercise a greater degree of project control as the design team cannot proceed to the next stage until the previous stage has been completed and approved and, as such, is much more of a process management model than a contractual model. The output of each stage is also 'frozen' to help improve cost certainty and to reduce the amount of abortive work and late design changes required. Interestingly, this project review approach is also an important component of a lean product development environment (Heilman, 1999). As well as defining design stages the model also incorporates a number of project activities which have to be performed. All activities can, but need not, occur in each phase.

3.3.3 Process Protocol

The RIBA model represents the construction design process from the architects' standpoint (Kagioglou et al, 1998) and the BAA model the client's view and, as such, both are questionable from a generic perspective (Sheath et al, 1996). The process protocol seeks to produce a generic model which encompasses the perspectives of all major participants.

	Phase	**Description**
Pre-Project	0	Demonstrating the need
Pre-Project	1	Conception of need

Pre-Project	2	Outline feasibility
Pre-Project	3	Substantive feasibility study & outline financial authority
Pre-Construction	4	Outline conceptual design
Pre-Construction	5	Full conceptual design
Pre-Construction	6	Co-ordinated design & Procurement and full financial authority
Construction	7	Production Information
Construction	8	Construction
Post Completion	9	Operation & maintenance

Process Management Activities

1. Development Management
2. Project Management
3. Resource Management
4. Design Management
5. Production Management
6. Facilities Management
7. Health & Safety, Statutory and Legal Management
8. Process Management

The model is broken down into ten phases: four pre-project, three pre-construction, two construction and one post construction, showing a particular focus to the front end of projects. The model also includes eight critical process management activities and attempts to indicate the sorts of tasks that have to be performed by them in each phase. Between each phase there is a 'gate' / project review. Gates can either be 'hard' or 'soft'. Where there is a soft gate between phases, phases can be performed concurrently, however, if there is a hard gate between phases, they must be performed sequentially, with progress to the next phase subject to the result of the phase review. The location of soft / hard gates is dependent upon where in the process substantial investment is required to continue the project (Kagioglou et al, 1998). This model is similar to the BAA model in that it seeks to control the process rather than merely represent the sorts of stages which take place. It is also similar to the BAA model as it includes process / project activities. The idea of two different types of gates distinguishes it from the BAA model and a greater number of design phases ensures a large number of reviews. The assessment of the design made during the review is obviously seen as very important component of the model and intrinsic to this is the feedback from the review to the project team. As stated earlier, this is important from a lean product development perspective. Another interesting feature is the ongoing review of the facility over its lifecycle.

The process protocol is faithful to the RIBA model in that it retains three distinct design phases but incorporates the BAA model approach by introducing a soft gate between phases four and five, and a hard gate between five and six. With regard to an underlying procurement route for the model it would seem that the process protocol is far more generic than the other two models considered. The model also attempts to map the types of IT that could be used in each of the phases.

3.3.4 Other Models

A number of other design models have been created with various objectives and about different aspects of design and are too numerous to mention in this thesis. Although it will not be considered in great detail, a brief mention should be made to those models that represent data structures in design for the purposes of creating computerised design support tools. This issue has been considered by a number of authors such as Kalay, Khemlani & Choi (1998), Li & Love (1999), Eastman & Fereshetian (1994) and De La Garaza & Alcantara (1995). This work often seeks to understand the design process and / or design thinking with a view to establish the most suitable way to develop systematised tools, and when they should be used by designers.

Another model produced by Alarcón, Ashley & Teicholz (1997) is an attempt to model mathematically the impact of early decision making strategies on the performance of projects. This provides decision makers with a means of evaluating different decision options and, as such, can be considered a predictive tool.

3.4 AXIOMATIC DESIGN

The axiomatic understanding of design was developed in the late 80s by Nam P. Suh and, as such, this section will draw exclusively on his work - 'The Principles of Design' (Suh, 1990).

Suh posits that the objective of design is always stated in the functional domain whereas the solution is generated in the physical domain. These two domains are said to be independent of each other and it is design that links them. Therefore to proceed with design, one must characterise design objectives in terms of functional requirements (in solution neutral terms) and the physical embodiment in terms of design parameters. The process of design is to map the functional space to the physical space. It is also important to note that intrinsic to this perspective of design is a hierarchical nature which can be decomposed. However, it is necessary to travel back and forth between the physical and functional domains to achieve this. Suh defines design as:

"The creation of synthesised solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the functional requirements in the functional domain and the design parameters in the physical domain, through the proper selection of design parameters that satisfy functional requirements."

The mapping process in not unique which leads to the assertion that an infinite number of plausible solutions can be generated. The axiomatic view of design is based on the question, 'as the designer maps between functional requirements and design parameters are there certain rules that are satisfied by good design?' Or, in other words, is there a scientific basis to good design? From this starting point, Suh suggests that there are two design axioms:

1. *Independence axiom*: maintaining the independence of functional requirements. As a designer maps from the functional domain to the physical domain, the mapping must be such that a perturbation in a particular design parameter must only affect its referent functional requirement.

2. *Information axiom*: minimising the information content of design. Amongst all the designs that satisfy the independence axiom, the one with the minimum information content is the best design.

From these axioms seven corollaries have been generated:

1. De-coupling of coupled design – de-couple or separate parts or aspects of a solution if functional requirements are coupled or become interdependent in the designs proposed.
2. Minimise the number of functional requirements and constraints.
3. Integration of physical parts if functional requirements can be independently satisfied in the proposed solution.
4. Use of standardisation or interchangeable parts.
5. Use of symmetry.
6. Use largest allowable tolerance.
7. Seek an uncoupled design that requires less information.

Suh also suggests that to be a good designer it is important to be able to identify only those functions which are absolutely essential, which requires an extensive knowledge base covering the design problem. This is an interesting insight as rather than contradicting Chan's (1990) 'ability to select rules in constraint schema' would seem to precede it, and be complimentary to it. Suh goes on to agree with Chan by suggesting that a good designer also needs to be able to identify constraints, or design boundaries. The development of the axiomatic view of design was largely generated within a mechanical context. However, this does not suggest that the axioms are limited to this particular discipline but rather, given their wording, they are likely to be applicable to design in general. The caveat that the author of this thesis adds, is that it is easy to conceive of mapping from functional requirements to design parameters for a mechanical system that is understood to be governed by particular mathematical relationships, however, it is less obvious to see how people's preferences can be accounted for in this way, especially if a particular preference moves the design away from an optimised solution, as can be the case in construction design. This in no way detracts from

Suh's achievements but rather highlights that the method is far from intuitive and would most likely be quite alien to architectural designers. Perhaps the most useful aspect of this work in relation to construction design is the corollaries that are derived from the axioms. These can be taken to be good design rules or guides which can be, in the most part, easily applied.

3.5 DESIGN FOR MANUFACTURE (DFM) / DESIGN FOR ASSEMBLY (DFA)

It is clear that the design stage of a project has significant potential as a means of improving the efficiency of the *total* construction process. Chen & McGeorge (1993/4) use the Pareto principle to show that upstream decisions have more potential to influence the final outcome than decisions taken further downstream. Indeed, Kochan (1991) goes as far as suggesting that the design phase defines 70% of the manufactured product. One of the techniques used in the manufacturing sector, Design for Manufacture (DFM) / Design for Assembly (DFA), is used to improve the manufacturablity of an article by matching the product being designed to the processes which are used to deliver it (Boothroyd, 1994). This is achieved using quantitative methods to compare alternative designs against an *idealised* solution indicating the efficiency of a particular configuration in terms of production cost and needs to be done as early as possible in the product life-cycle (Suh, 1990). The underlying philosophy of DFM is to provide knowledge of downstream processes to designers to improve the design decision making process. In some instances quantitative methodologies have been established and systematised, for example the Hitachi, Boothroyd and Lucas approaches (Leany & Wittenberg 1992). These compare alternative designs at the component level to rate the design efficiency. The methods are used to simplify designs with a view to reducing the total production costs whilst fulfilling all the functional requirements. Interestingly, this approach appears to be consistent with Suh's (1990) design corollaries (see section 3.4), as the systematised DFA tools seek to simplify designs by reducing the part count by combining parts that do not have to be separate for particular reasons. DFM tools seek to incorporate part symmetry and standardisation, amongst other means of reducing manufacturing costs.

3.6 CONSTRUCTION DESIGN METHODS / APPROACHES

In chapter 2 of this thesis an in depth study of the application of lean thinking to construction design is presented. As part of that chapter BPR and concurrent engineering were also considered because of their similarities to the lean thinking paradigm. As these approaches to construction design have already been detailed elsewhere they will not be repeated in this section. However, three other techniques are worthy of inclusion: constructability, value management and value engineering.

3.6.1 Constructability

Constructability, or buildability, the terms are used interchangeably in the literature, refers to the capability [of a building] of being constructed (Construction

Management Committee of the ASCE Construction Division, 1991). The Construction Industry Institute (CII) (1986) define constructability as 'the optimum integration of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall project objectives'. There is a difference between these two perspectives, particularly with regard to objectivity, which will be explored through a third definition. Patty et al (1995) define constructability as 'the integration of construction knowledge and experience during all phases of the facility development process', with the objectives of improving construction and overall performance. It is the objectives of constructability, often implicit to the definitions, which is of particular interest. The author of this thesis takes the view of Patty et al (1995) that constructability is principally a means of improving project performance by producing design solutions that are easier to build. Constructability *per se* does not set out to achieve overall project objectives, this is the remit of the total construction process. Constructability is one characteristic of design solutions that meets *some* project objectives and is in dynamic tension with other characteristics such as fitness for purpose – functionally speaking, aesthetic requirements, cost, programme, etc., that seek to address other requirements. Trade offs need to be made between all these characteristics to achieve the overall project objectives. The author of this thesis takes this view to prevent the 'ease with which a design solution can be constructed' from being subsummed within the total construction process, which seeks to meet the overall project objectives. It needs to be distinctly defined to receive adequate attention. This echoes Chen & McGeorge's (1993/4) definition, 'as the extent to which decisions made during the whole building procurement process, in response to factors influencing the project and other project goals, ultimately facilitate the ease of construction and quality of the project'. The authors go on to say that buildability can be maximised where buildability objectives do not conflict with other project requirements by drawing upon construction knowledge, team skills and innovation, at the right time and by the appropriate agents. Their definition was made in response to the view that constructability problems are largely due to the separation between design and construction (Chen et al, 1996). A number of authors cite this as an issue (Lautanala, 1995, Moore 1996(1), Moore, 1996(2), Alshawi & Underwood, 1996) with varying degrees of conviction that it is the most important factor in producing design solutions which are difficult to build. However, Chen & McGeorge (1993/4) take the stance that this is an inadequate view of the causes of poor constructability. They accept that it is an important factor but other issues such as decisions which are made upstream of the design stage, documentation, contractor selection, procurement route and a number of factors outside of the control of the design team, such as political agendas, may all impact the constructability of a building. Chen & McGeorge develop a systems view of the design-construction process which may help to neutralise some of the negative influences on constructability. Moore (1996(1)) stresses the lack of knowledge sharing as a particularly important issue, as does the Construction Management Committee of the ASCE Construction Division (1991). But even if this knowledge sharing did take place, Patty et al (1995) suggest that there are few construction professionals who have sufficient design expertise to function effectively as constructability experts. This point, of course, is debatable, and is considered to be quite severe by the author of this thesis. Perhaps the biggest problem would not be construction professionals' lack of design knowledge, as this can, and should, be provided by design experts, but rather how these two disciplines interact and communicate their ideas and knowledge to each other and, indeed, when these exchanges should take place. Moore (1996(2)) also sees the modern role of the architect as being a significant factor of poor constructability.

In its simplest form, constructability improvements can be achieved by making greater use of standardised components / methods and by seeking to rationalise design through repeatability, where appropriate. Interestingly, these ideas can be found in Suh's (1990) design corollaries (see section 3.4). Although, Moore (1996(1)) warns that a buildability strategy that seeks to impose predetermined construction solutions will not be readily accepted by design professionals. Moore has in mind standardisation and project level simplification. A number of other suggestions have been made in the literature as to how the constructability of buildings can be improved. Some offer generic solutions whilst others for more specific situations. Alshawi & Underwood (1996) have developed an automated tool for designers to improve the integration between design and construction for mid-rise reinforced concrete office developments. Moore (1996(1)) has developed an automated design aid for constructability based on the modelling of skills required by specific construction tasks. This allows design options to be compared on the basis of the degree of skill required to construct them. This should lead to simplified designs as difficult to construct elements will be identified. Interestingly, Bishop (1985) notes that it is design, especially detailed design, which determines the skills that will be required. Luiten & Tolmen (1993) posit that a big problem lies in the fact that there are no means of assessing buildability during design and that design teams revert to common sense. They suggest a Building Project Model (BPM) as a means of solving constructability issues. The authors posit that this requires an internationally accepted standard for exchange of project information because of the complexity of the rules / databases on information required to make Design For Assembly (DFA) type rules for construction. Glavanich (1995) suggests two methods for increasing the efficiency of design and improving constructability: (1) design phase scheduling – creating a construction schedule during the design phase which is continuously reviewed and updated as design progresses and (2) a design phase constructability review – a review process that specifically assesses the constructablity of the proposed design solution. Lautanala (1995) also includes in his model a specific constructability assessment task with predefined constructability assessment criteria – unfortunately the criteria were not specified. O'Connor (1985) suggests that the likelihood of delays can be decreased by increasing the availability of engineering information, the amount of construction manpower required can be decreased by combining design elements and seeking optimal construction systems such as modularization and that construction activity duration may be decreased by using optimal construction systems.

The use of DFM / DFA type approaches in manufacturing led to significant improvements in manufacturing and assembly costs. The same is reputedly true for construction companies employing constructability type thinking in their projects. In their investigation, Russell et al (1994) considered four case studies using three different constructability techniques: use of a construction management firm during pre construction, specialised formal programming and comprehensive tracking. They found that all three methods generated a 10:1

benefit to cost ratio. The authors thought these figures were an underestimate of the total benefits as they do not include all the qualitative improvements derived from using a constructabilty approach. O'Conner (1985) suggests that the six most significant cost saving impacts that good constructablity leads to are:

1. Decrease in the likelihood of delays.
2. Decrease in the amount of required direct construction manpower.
3. Decrease in the duration of a construction activity.
4. Decrease the amount of work at high elevations.
5. Decrease the quantity of materials required.
6. Decrease the likelihood of labour problems.

Similar types of benefits are outlined by Luiten & Tolman (1993) and Chen et al (1996). Luiten & Tolman also include improved profitability of the construction process and improvement in the quality of the product.

3.6.2 Value Engineering / Value Managment

Whilst constructability deals with the ease of construction value engineering / value management deals with satisfying functional requirements at the cheapest possible cost. An important issue in understanding value engineering / management is that value and cost are two different phenomena. McGeorge & Palmer (1997) suggest that where all functions are achieved at the lowest cost, there is good value. Where function is achieved at too great a cost, there is little or no value. Green (1989) defines value engineering as 'a systematic approach to provide the required function at the lowest cost'.

The term value engineering was first used by Miles to describe a technique that he developed in the 1940s. At the heart of this approach is functional analysis. Functional analysis is a method of describing functional requirements in terms of one verb and one noun and then using these descriptions to generate alternative design solutions which fulfil the functional requirement. Each solution is evaluated in terms of the lowest possible cost to achieve the desired function. The basic philosophy of value engineering is thus to eliminate the cost which does not contribute to the performance of the required function (Green, 1989).

There is some debate of the use of terms in the literature. McGeorge & Palmer (1997) refer to Miles' view of value engineering as value management. This is because the US system of value engineering does not include functional analysis and has therefore departed from the original work of Miles. The reason for this is that most of the value engineering work in the US relates to government projects, all of which follow the approach developed by the Department of Defence. As such the US system has been claimed to be a design audit and not a value management technique (Palmer, 1995). For McGeorge & Palmer (1997) then, functional analysis is a vital aspect of value engineering / management. However, Green (1994) suggests that value engineering and value management are two different aspects of the same overall approach. This suggestion is based on the author's identification of two assumptions which are often made when considering value engineering:

1. Function is an objective characteristic waiting to be revealed.
2. All identified design solutions provide the same level of functional performance and can therefore be evaluated on the basis of cost alone.

Green (1994) states that these assumptions are justified at the component level but are less reliable at other levels McGeorge & Palmer (1997) suggest four levels at which value management can be applied: project, space, elemental and component). The higher the conceptual level the less reliable they become. A factor effecting this issue is that the higher the conceptual level the more functional requirements a particular attribute will have to fulfil. As such, Green suggests the following definitions for value engineering and value management:

'*Value engineering* is concerned with achieving a given function at minimum cost. It is based on the assumption that function is an objective characteristic which is waiting to be identified. Furthermore, it is assumed that all feasible design alternatives provide the same level of functional performance and can therefore be assessed on the basis of cost alone. Within this frame of reference, an increase in value can be directly related to a reduction in cost.'

'*Value management* is concerned with defining what 'value' means to a client within a particular context. This is achieved by bringing the project stakeholders together and producing a clear statement of the project's objectives. Value for money can then be achieved by ensuring that design solutions evolve in accordance with the agreed objectives. In essence, value management is concerned with the 'what' rather than the 'how'.

From these definitions it follows that value engineering is about building efficiency and value management is improving the effectiveness of briefing. The former is used in the later stages of design and the latter in the earlier stages. The application of value engineering / management has led to cost reductions. Palmer (1996) found from a number of case studies that the average proposed savings were approximately 33% of the total project cost. However, it was also found that an average of only 11% of these savings were implemented. Acharya et al (1995) suggest that savings can range from between 5 - 30% of total project cost.

3.7 CONSLUSIONS

Design in construction is a highly complex process which deals with ill defined problems. Integration between disciplines is a key issue as the break between design and construction is seen as a contributory factor in the poor constructability of buildings. Poor constructability is another type of waste in the total construction process which is undesirable from a lean thinking, and indeed, any stakeholder perspective. In the first instance, Suh's (1990) axiomatic design approach could be used to improve constructability by simply applying the design corollaries. This is contrary to Moore's (1996(1)) position that design professionals would not readily accept the use of standardised components and symmetry, etc. However, 'readily accept' and 'use' are two different concepts. Designers may be forced into a position where they have to use these ideas because of economic factors created by increased competition in the market place. Design is perhaps the most influential process in the total construction process and British construction designers will have to become increasingly commercially aware as the market changes. They must learn to adapt the design process to respond to the pressures that competition brings. A lean design environment could incorporate constructability and value engineering / management approaches to help reduce waste, the former by making buildings easier to build, the latter through making cost savings without compromising functional requirements. It was far from conclusive, however, which constructability approach is best and, indeed, whether all the major concerns have yet been addressed. Perhaps a first step could be to include construction professionals at the beginning of each project whilst more research is conducted into constructability assessment methods. Similar tools to Boothroyd's DFMA analysis package, which is used in manufacturing, could help to reduce production costs and therefore increase the profitability of the construction process. Use of value management at the briefing stage of construction projects, and value engineering in the later design stages may offer the most comprehensive approach to addressing functional requirements, and should help the voice of the customer to be heard throughout the design process.

Two types of models have been considered in this literature survey: psychological models which focus on the individual designer and macro models that reflect the entire design process from a product development perspective. The psychological models attempt to identify (1) how the designer thinks and (2) produce systematic frameworks, which if followed, should lead to good design. An issue that arises is to what extent is it possible to use these models as a form of best practice or a recipe for design that leads to consistent and high quality design solutions. The debate hinges on what aspects of design can be taught and what aspects are solely the function of a persons intelligence. An interesting factor in this contention is the role of experience. It has been found that knowledge of a specific problem type effects the design process as memory plays a greater role. This might suggest that following a framework or model could facilitate those flashes of inspiration which are an intrinsic part of creativity, and so little understood. However, there are likely to be some qualities which are intrinsic to the person which will play a key role in determining the successful outcome of design, regardless of the framework employed. An interesting observation from the psychological aspects of design is that architects tend to think about design problems through the development of solutions. However, Lloyd & Scott (1994) suggest that this is a characteristic displayed by designers, regardless of discipline, who have experience of the specific problem type. If architects normally approach design in this way an inference could be made that construction projects have enough commonality between them, such that, previous general experience constitutes specific problem experience. The approach to design is also likely to be a function of training but, nevertheless, it is an interesting thought which could have implications for lean construction design, especially with regard to a standardised approach to product development.

A number of macro models have been developed which both reflect design activity and seek to control the design process, to varying degrees. Two models in particular, which have been influenced by product development models in the manufacturing sector, seek to apply process management through a staged review process. These are the BAA model and the process protocol. However, neither of these models is widely adopted by the construction industry. The most common model is still the RIBA approach, which acts to facilitate contractual obligations rather than apply process management principles. From a lean thinking perspective, models that seek to manage the design process are more desirable as they (1) help to standardise the approach and (2) utilise project reviews to improve product design. Project review is an important component of lean design thinking. Use of the process protocol in a lean construction environment would offer the control benefits of the BAA model but would not restrict it to a partnering framework agreement. The process protocol appears to be a more generic approach with regard to procurement route. This idea of standardising the approach to the design process will be explored further in the work that follows. This concept is intrinsic to lean thinking and from the literature there are suggestions that it might be feasible despite the commonly held notion that every construction project is unique. Undoubtedly this is true, but the question remains, how unique, or to rephrase, how much of construction design is generic?

A number of views of design have been presented which have to be taken into account if the lean thinking approach is to be applied to construction design successfully. Because of the diversity of design perspectives, it is clear that design is highly complex and as such cannot easily be described and labelled. It can also be viewed at a number of different levels, from the individual designer through to the total process relating all design disciplines to tasks and resources. The application of lean thinking to construction design is likely to take place at this organisational or process level, however, undoubtedly it will impact the working methods of individual designers in some way, although it is unlikely to affect their cognitive processes. To implement the lean thinking approach the starting point of this research should be to identify waste in construction design and make an assessment of the impact that it has on projects. It is also important to gain further insights into the design process in construction projects to establish a clearer view of the mechanics of design, and how lean thinking might make it more efficient and efficacious. This can be achieved through a detailed mapping exercise of the design process.

The next chapter outlines the research approach taken by this study.

CHAPTER 4 RESEARCH OUTLINE

> *"It is difficult because it [the briefing process] is not more defined and I am sorry that it is not more defined, but it is actually quite a loose process and we are expected to use our sense and judgement to get where the client expects us to get to."* **Peter Griffiths, Stanley Bragg Partnership.**

CHAPTER 4 RESEARCH OUTLINE 61
4.1 FROM THE LITERATURE SURVEY... 62
4.2 IDENTIFYING WASTE IN CONSTRUCTION DESIGN 62
4.3 ELECTRONIC DATA GATHERING TOOL (EDGT) 64
4.4 MAPPING THE DESIGN DECISION MAKING PROCESS 64
4.5 DESIGN DECISION PLANNER 65
4.6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK 65
4.7 RECONCILING RESEARCH TO THE LEAN THINKING PARADIGM 65

4.1 FROM THE LITERATURE SURVEY...

Design is a highly complex process which is far from being fully understood. It is a process of generating ideas that fulfil a set of predefined functional requirements through creative thought. It is perhaps least understood at this psychological level despite considerable research through protocol analysis. This is hardly surprising due to the intricate nature of the human brain and the lack of knowledge of cognitive processes in general. In the industrial setting, however, sociological issues play an important role as most commercial design is undertaken by design teams. Additional constraints such as time and cost also become important factors as the client has needs other than functional requirements (of the building). At the organisational (or process) level it is possible to enhance the quality and / or speed of design by the approach implemented. The components of the design process and the order and timing of these components can either facilitate or hinder the efficiency of product development. One such approach is lean thinking.

The lean thinking paradigm suggests a five step change management approach that can make organisations lean:

1. Understanding what the client *values.*
2. Identify and remove waste within the organisation by analysing the *value stream.*
3. Facilitate value *flow* through the organisation.
4. Value should be *pulled* through the processes, initiated by the client.
5. Continuous improvement – *strive for perfection.*

Five factors have also been identified that directly relate the lean philosophy to the product development process:

i. Single leader responsible for the product.
ii. Multidisciplinary teams, co-located where possible.
iii. Clearly defined responsibilities for all team disciplines.
iv. Standardised approach to product development.
v. Ensure that the voice of the customer is heard throughout the product development process.

It is elements from the change management approach and factors relating lean thinking to the product development process that this work seeks to apply to construction design.

4.2 IDENTIFYING WASTE IN CONSTRUCTION DESIGN

The second objective stated in section 1.4 is to assess the potential benefits of applying lean thinking to construction design. This was achieved, in part, through the literature survey which outlines some of the benefits companies have received by applying the lean philosophy (see chapter 2). However, these benefits were not just a result of making one process lean but rather the entire organisation. Also, these companies tended to be in the manufacturing sector and, as such, might display different characteristics to construction corporations. It was necessary, therefore, to consider what impact lean thinking could have directly on construction design. It was decided that this could be achieved, in part, by considering how much waste existed in construction design and how much money could be saved by eliminating this waste.

An initial investigation identified change orders as a type of waste in the construction design process. Change orders can be considered to be the consequences of poor or incorrect design decisions. In order to investigate the significance of this phenomenon, and hence gain insights into the amount of waste in the design process, it was decided to examine historical data from a number of case studies. It was anticipated that the study would provide an indication as to the size of the opportunity for applying lean thinking to construction design. It was not considered to size the entire opportunity, as change orders only constitute one type of waste. Rather, it was thought that the study would calculate the magnitude of one component of the total opportunity. From this, inferences could be made either to the extent of the magnitude of waste in the design process, or to the value of proceeding with this line of enquiry – the application of lean thinking to construction design.

The use of historical data was chosen because of its availability and accessibility through the project's industrial partners. It was decided to use the case study approach as the research was essentially exploratory, with numerous data types for each project under investigation. Also, little was found in the literature regarding change orders, so there was no guidance as to which factors could be of interest.

This investigation found that significant sums of money in construction projects are lost because of design mistakes, and poor, or incorrect, design decision making. This result was also considered to be an underestimate of the real cost to projects because of the limitations of the data collected and the choice of case studies used. As change orders are only one type of design waste, it was deemed that significant potential for cost savings existed through the application of lean thinking to construction design. It was also found that a lot of the problems in design related to process issues. That is, issues which can be directly influenced by the design team. Because of this finding, it was realised that an investigation of the design decision making process was required. Change orders are the consequences of design decisions and are therefore symptomatic, the real malaise exists in the design decision making process. However, two research options were open at this stage: (1) try to identify root causes of change orders and eliminate the cost to projects and (2) take the notion of change orders as a general 'sickness' of the design process, and then do further investigations to try to identify the factors which will lead to improved design control. The latter of these two options was chosen.

To investigate the design decision making process in construction design an Electronic Data Gathering Tool (EDGT) was developed.

4.3 ELECTRONIC DATA GATHERING TOOL (EDGT)

A series of interviews with architects and findings in the literature led to the conclusion that the design decision making process should be mapped at the system / sub-system level. The literature also provided the insight that decisions at this level have the most impact on the cost of a product. The EDGT was designed on the basis of information provided in the interviews. These interviews provided the first insights into construction design and identified what aspects of the design process should be captured. The architects also provided suggestions for the systematisation of the EDGT, and how it should be implemented. The tool was systematised into Microsoft Access 97™. The tool was not developed to capture information about individual designers' thought processes but, rather, to be used at the level of interaction between design disciplines.

The EDGT was used on three live construction projects to capture information about design decision making at the system / sub-system level.

4.4 MAPPING THE DESIGN DECISION MAKING PROCESS

The investigation of the change order request system established that significant savings can be made in construction projects by improving the design process. Change orders, however, are only symptoms of the real problems that exist and as such the design decision making process needs to be investigated in some depth to identify the root causes of design problems. Mapping the design decision making process with the EDGT is a first step in trying to identify the issues involved in design efficiency and the application of lean thinking concepts.

The research approach for this study was also case study based. The investigation into design decision making was highly exploratory trying to encompass a large number of factors due to the complexity and uncertainty involved in design. No historical data was available that would provide the depth and breadth of information required to give adequate insight into design decision making, hence the need for the EDGT. Live construction projects were used as design issues were still fresh in the minds of those people involved in the data collection exercise. Each person collecting data was intimately involved in the decision making process for each of their respective projects. Yin's (1984) treatise on the design of case study research was used to help shape the approach. From the data, it was possible to investigate the distribution of decision making across projects, identify who made each decision and which other disciplines supported the process, what constraints were identified and the consequential reason drivers used to choose between design options. It was also possible to establish the level of cost and programme visibility that the design team had when making each decision.

Examining the case study data revealed that, in most instances, little formal design planning takes place. This was identified as a hindrance to making construction design lean.

The maps produced can be considered to be value generation maps, which are a subset of Womack and Jones' (1996) 'value streams'. From the maps, it was found that there are a large number of generic design decisions across construction projects at the system / sub-system level. As an important principle of applying lean thinking is to try to standardise the product development approach, the discovery of a large set of generic design decisions in construction design led to the development of a design planning tool which has been called Design Decision Planner (DDP).

4.5 DESIGN DECISION PLANNER

Design Decision Planner (DDP) is a means of planning construction design at the system / sub-system level on a design decision basis. It allows the design team to list, order and specify the timing of design decisions for the early stages of design. Measuring progress against planned design provides a useful metric from a project management perspective. The tool is described in longhand form but could easily be systematised to enhance its capability. At the core of the tool are the decisions that were identified in the value generation maps, with the associated process information. This assists the design team with identifying the relevant decisions that will have to be made for a particular project and makes design planning at this level of detail a realistic proposition. Other information contained in the maps can assist with assigning responsibility for individual design decisions to particular disciplines and the information sources that have to be investigated.

4.6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The lessons learnt from the study are drawn together with reference to the broad objectives of the work. Recommendations are then made for future endeavours of applying lean thinking to construction design.

4.7 RECONCILING RESEARCH TO THE LEAN THINKING PARADIGM

Figure 4.1 shows the main generic research stages, from the 'need' and 'problem specification' to 'recommendations' for improving construction design on the basis of the lean thinking paradigm. Also shown are the main research components (change order request analysis, etc) and Womack and Jones' (1996) five steps for the implementation of lean thinking. The link to lean thinking in this sense is somewhat tenuous as the five steps are for organisations that want to transform themselves in to a leaner entity. As such, the five steps constitute a change management model that Womack and Jones promote as the way to ensure successful implementation of lean thinking. From a research perspective, however, it is the lean principles, such as those described in section 4.1, that are of greater interest. Nevertheless, the stages of the research project do reflect some of those steps, if not quite the way intended by the Womack and Jones.

'Specifying value' relates to what the customer values in the product. As there was no specific product at the outset of this research and no client as such, the voice of the customer has been related to the likes of Egan and Latham who have identified deficiencies in the industry and have suggested ways in which improvements can be made. This has been identified with the research 'need'. One of the areas of deficiency noted is the design process. The design process was also identified as having significant potential to influence the outcome of the total delivery process and, therefore, worthy of further study from a process improvement perspective. Design was thus considered to be the 'specified problem'.

The two main data gathering and analysis phases in this study have been related to 'value stream' mapping. 'Value stream' mapping is a technique that allows the tasks in an organisation to be visualised and then grouped on the basis of those which add value to the product, and those which do not. The investigation of the change order request system, can be thought of as the identification of a waste type in construction design, and also as a means of assessing the size of the opportunity that exists to make construction design leaner. Thus, it is closely related to the 'value stream'. The second analysis, mapping the design decision making process, is perhaps even more closely related, as these maps can be thought of as the value adding part of the value stream maps and, as such, could be called value generation maps.

In figure 4.1 the mapping of the design decision making process and the analysis of the data have been split, with the analysis part indicated as being analogous to 'flow' in the lean thinking paradigm. This is perhaps the most tenuous aspect of the reconciliation between research components and the five steps to becoming lean. 'Flow' is about the reorganisation of tasks to help value flow through the system. This idea was linked to the analysis as the results of the study will lead to a leaner approach to construction design. Another somewhat tenuous link is the concept of 'pull' with that of the Design Decision Planner (DDP). In manufacturing the idea of 'pull' is that upstream processes, or tasks, are not performed until down stream processes indicate that there is a need to do so, with the initial tug coming from customer orders, or forecasted demand. The DDP does not quite emulate this, however, it does prompt the design team to make certain design decisions within particular design periods.

'Perfection' is the ongoing efforts to improve construction design and in this study relates to the recommendations for further work.

Figure 4.2 provides an outline of the rest of the thesis, relating research components to particular chapters and the logical links between stages.

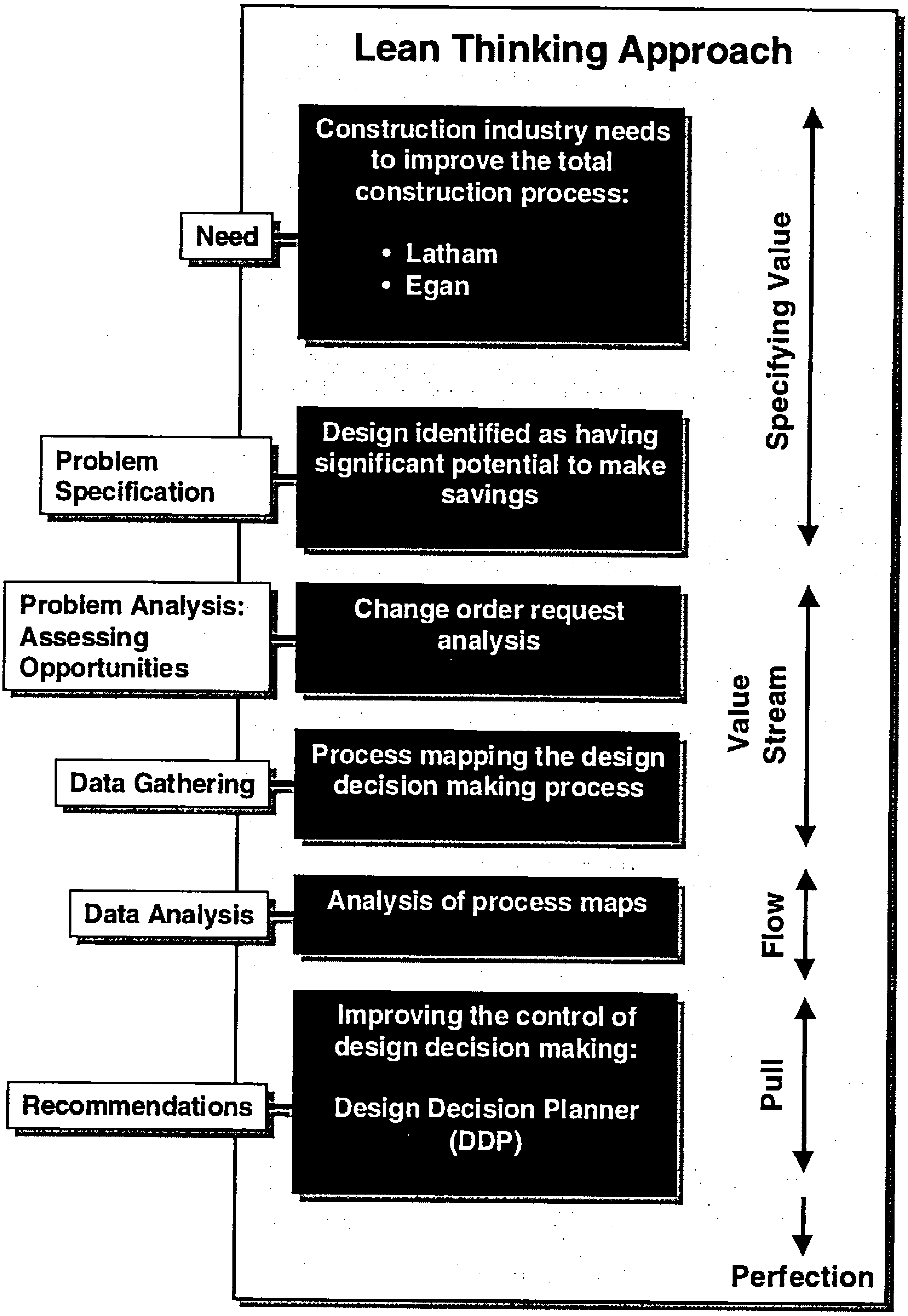


Figure 4.1 – Research Stages and the Lean Thinking Paradigm

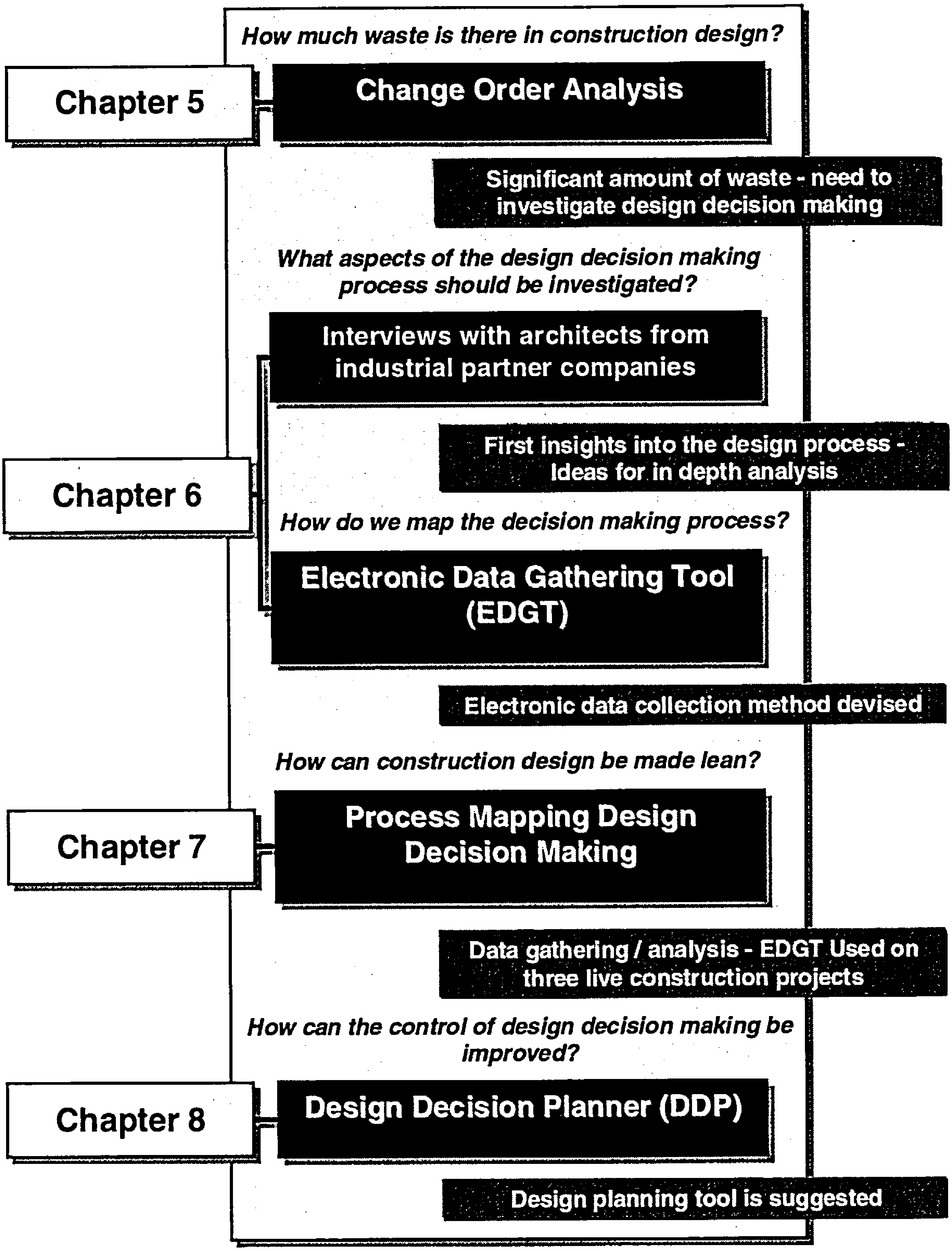


Figure 4.2 – Research Components and Their Respective Chapters in this Thesis

CHAPTER 5 IDENTIFYING WASTE IN CONSTRUCTION DESIGN

> *"Any time that we modify anything they [contractors] are going to put in a claim. Now we are seeing that the more sensitive things are the finishes of the building. They're proposing different materials than were specified. So I write in the order of ten to fifteen rejections a week on everything that they issue. It's a war of attrition. Then I have to give an explanation...justification for each rejection. It is kind of a balance between allowing them to get away with this sort of finish or this piece of kit, but there are other things that we'll just not even negotiate."*
> **Etienne Borgos, Sir Norman Foster and Partners (regarding change orders).**

CHAPTER 5 IDENTIFYING WASTE IN CONSTRUCTION DESIGN 69
5.1 INTRODUCTION 70
5.2 OBJECTIVES 71
5.3 CHANGE ORDERS 71
5.4 THE CHANGE ORDER REQUEST SYSTEM 72
5.5 ANALYSIS OF CHANGE ORDER REQUEST DATA 74
5.6 OVERVIEW OF THE CASE HISTORIES 75
5.7 CHANGE ORDER REQUEST RESULTS FOR CRANFIELD UNIVERSITY LIBRARY 80
5.8 CHANGE ORDER REQUEST RESULTS FOR HEATHROW CARGO WAREHOUSE 94
5.9 CHANGE ORDER REQUEST RESULTS FOR MARKS & SPENCER PRESTON 104
5.10 DISCUSION 109
5.11 CONCLUSIONS 116
5.12 SUMMARY 117

5.1 INTRODUCTION

In the light of the literature survey it is clear that the design stage of a project has significant potential as a means of improving the efficiency of the *total* construction process. Chen & McGeorge (1993/4) use the Pareto principle to show that upstream decisions have more potential to influence the final outcome than decisions taken further downstream. Indeed, Kochan (1991) goes as far as suggesting that the design phase defines 70% of the manufactured product. Whilst the literature survey verified the possibility of improving the total construction process by focusing on design, it did not provide a good indication as to the magnitude of the opportunity. It was decided, therefore, that an exploratory approach should be taken initially, to attempt to quantify the efficiency of the design decision making process in construction. This is consistent with Li's (1998) observation that, as a first stage to process improvement, it is imperative that a detailed study of existing processes should be conducted to identify deficiencies, and hence areas of opportunity.

The complex nature of the contractual chain in a construction project and the lack of continuity of staff (and organisation) from project to project means that it is difficult to find reliable, quantitative data on the factors which determine the consequences of design decision making. An initial study identified change orders as a reliable existing measure of the occurrence and cost of design changes which take place during the construction cycle. Change orders are often well documented because of the contractual implications involved. Therefore, as the only credible alternative identified, it was decided to process map the change order request system. This consisted of an historical examination of data generated by the system for a number of case studies. The data was provided by the industrial partners, together with access to key personnel involved in the projects. The personnel were available for consultation as to the nature of the system and the quality, completeness and verification of the data. The approach was to reverse-engineer the case histories in order to determine what *actually* happened to the design during the construction process, and some of the consequences of this.

The use of case studies in this instance rather than a statistical sample was due to the fact that little work was found on change orders in the literature. This means that key factors contributing to the need for change orders and their impact to projects had not been previously identified. Hence, there is little value in guessing at a small number of factors / variables and investigating them with an appropriate statistical sample. Using the case study approach allows a larger number of issues to be considered, although is unlikely to provide sufficient evidence of causality beyond the examined data. Case studies are therefore better suited for the purposes of providing first insights into the effects of change orders on construction projects. A statistical method may provide more conclusive findings, however, to be utilised effectively a reasonable knowledge or familiarity of the factors affecting design efficiency is presumed. To guess at factors affecting design efficiency and the need for contract issue design changes would be a high-risk research strategy that would have been unlikely to prove fruitful.

5.2 OBJECTIVES

This study set out to identify how design evolution, development and modification affect the total construction process and the delivery of a building as a product, in a quantitative manner. This was achieved by investigating the consequences of design decisions (change orders) and identifying what the implications are for the decision making process. Previous research established that contract issue design changes adversely affect construction projects. Thomas and Napolitan (1995) found that change orders reduced labour productivity by an average of 30%, although some changes could be made without loss of efficiency. Krone (1993) found that the Environmental Protection Agency (EPA) in the US had to request additional information on 40 to 50% of change submissions due to inadequate documentation. Machowski and Dale (1995) established that there are large administration costs associated with engineering changes. Although this work provides insights into the nature of change orders, it does not adequately show what the cumulative effects of contract issue design changes are on a construction project. The construction industry itself uses the system to consider the merits of each proposed change on an individual basis. This limits the visibility of the design team to assess the overall impact that change orders are having on their project. The true impact is *beyond the horizon.*

With these issues in mind, this study set out to identify:

1. The cumulative effects of change orders on a construction project?
2. Why change orders occur?
3. Which work packages are most commonly effected and why.
4. The implications for the design decision making process.

5.3 CHANGE ORDERS

There is some debate as to what constitutes a change order. The debate centres around the distinction between what constitutes design development and waste in the process. In other words, when does it start to cost the project money? The definition used by the author at the beginning of this section is that a change order is a *contract issue design change.* That is a design change which usually takes place after the tender has been awarded. The Royal Institute of British Architects (RIBA) (1992) Standard Form of Agreement for the Appointment of an Architect provides a commonly used model for structuring construction projects (see section 3.3.1). The key question defining whether a change order constitutes design evolution or waste is to what extent does the tender action in stage H *freeze* the design? This issue relates to the *cost certainty* of the project. Any change hereafter is likely to have a significant impact on the cost of the project which, ultimately, is passed on to the client.

The understanding of change orders in the construction is that they are a necessary part of the design process to accommodate design development and the changing needs of the client in the later stages of the *total* construction process. Interestingly, there is not a large body of writing on the subject of change orders. Perhaps this is because they are seen as a means of design development and are therefore not worthy of further study in academia? One of the motivations for this investigation was that the author did not share this view. Instead, it was assumed that the need for a design change is evidence of an incorrect (or incomplete) original design decision and therefore analysis of such changes should provide insights into issues that relate to design efficiency and efficacy. This stance suggests that change orders are more akin to rework, albeit rework of the design process, than design development. Rework in the manufacturing sector is the subject of close scrutiny as there is an associated cost with waste. From a *lean* manufacturing perspective, activities which constitute waste, should be eliminated to maximise the potential to add value to the product (Ohno, 1978). Huovila, et al (1994), adds a further contribution to the debate. The authors suggest that a proportion of conversion activities in the design process, namely rework due to errors, omissions and uncertainty are also waste and should therefore be removed. Also, the kernel of DFM thinking is to match the article being produced to its delivery processes. It was hypothesised that if there are a large number of contract issue design changes in construction projects, this would be an indication that the product (buildings) are not well matched to their delivery processes. This sets the agenda for the need to investigate the change order request system to provide insights into the cumulative affects of contract issue design changes on construction projects.

5.4 THE CHANGE ORDER REQUEST SYSTEM

The Change Order Request (COR) system is a standard project management tool for requesting and approving contract issue design changes in a controlled manner. Figure 5.1 shows the normal procedure for requesting change orders. This particular diagram was produced from the Project Team Procedures Manual (Section 13): Monitoring and Issue of Works Contractor Instructions, for the building of the library at Cranfield University. An equivalent procedure was used in other projects examined so figure 5.1 can be considered generic.

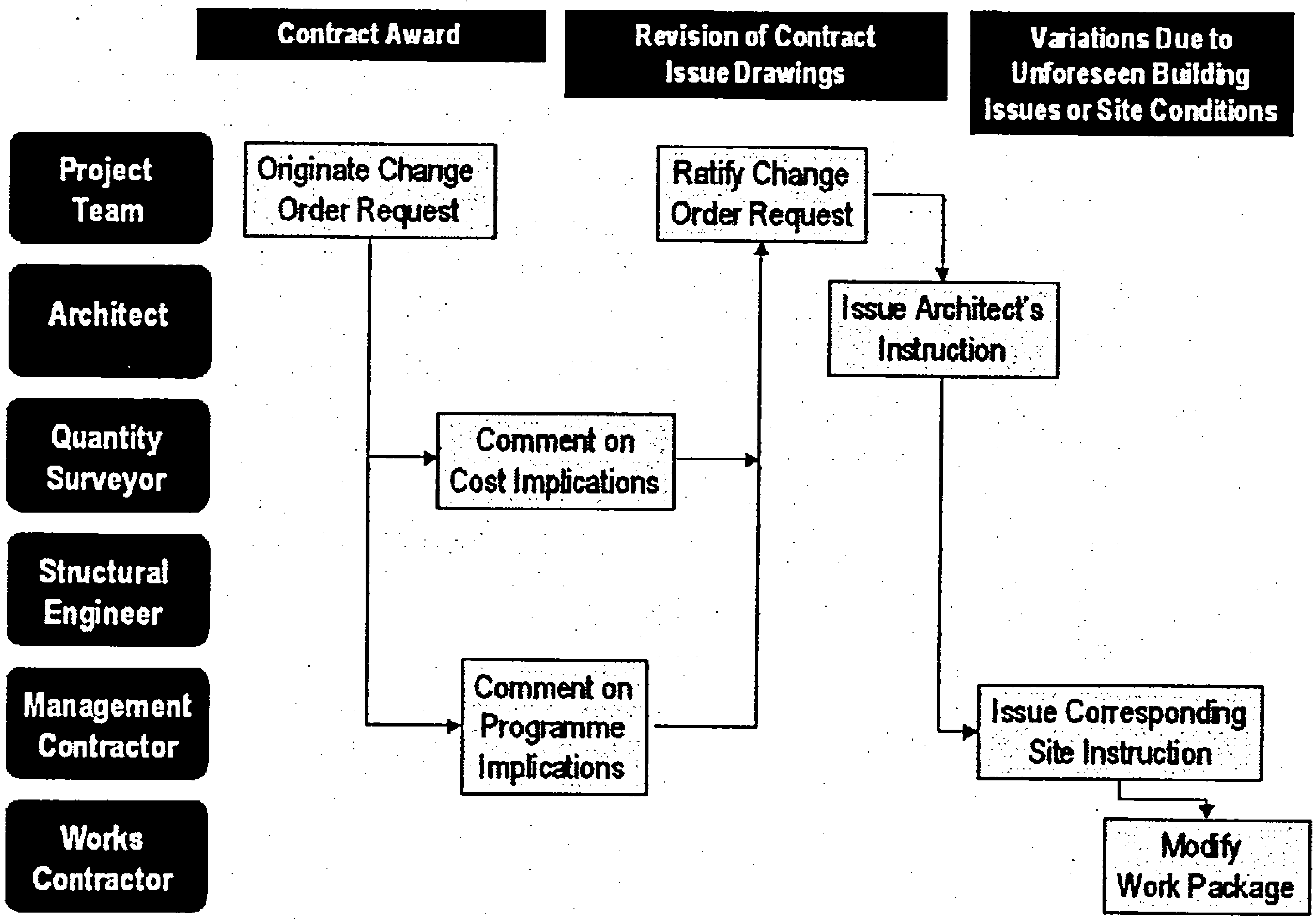


Figure 5.1 - Project Team Procedures Manual (Section 13): Monitoring and Issuing of Works Contractor Instructions

Each change order is considered on an individual basis to determine its likely impact on the construction project. The originator of the design change completes the appropriate documentation and submits it to the design team. The request is passed to the quantity surveyor and management contractor who comment on cost and programme implications respectively. On the basis of this information and an evaluation of the need for / potential to add value of the change, the design team make the decision to approve (or reject) the request and make any alterations to the contract issue drawings as required. The architect then issues an architect's instruction, the management contractor issues the corresponding site instruction and the work package is modified accordingly by the works contractor.

The data recorded by the system includes a description of the requested change, *who* - the originator of the design change, *when* - when the change was requested, *what* - which work package(s) it affects, *why* - the reason why the design change was requested, and the *consequences* - the consequences in terms of cost and programme implications. The description of the requested change consists of a few lines of text often making reference to contract issue drawings or other documents. The *originator* can be any member of the extended design team and has the responsibility of completing the request form. The *originator* identifies him / herself both by name and employer. *When* the change was requested is a date with a resolution of one day (in most cases). *What* work packages are affected by the change are recorded both by code and description. This field can accommodate changes which affect a number of work packages simultaneously, however, in the vast majority of cases in the data examined, affected only one work package. The reason *why* a contract issue design change has been requested is recorded by selecting the appropriate reason category on the change order request form. These options are part of the change order request system and were defined by the management contractor. They are high-level reason categories and as such do not provide the specific reason why a design change has been requested. Nevertheless, it is informative to assess 'cause' at this level in the first instance. The potential *consequences* of the change order are assessed by the management contractor and quantity surveyor. These are recorded in the form of an amount of time (e.g. number of weeks) and sum of money in pounds sterling, they may also be accompanied by other relevant comments. It is interesting to note that in the data examined the consequences were only recorded in terms of cost, even though facility was provided to record programme implications.

5.5 ANALYSIS OF CHANGE ORDER REQUEST DATA

The Change Order Request project management tool in itself provides some insights into the effects of individual change orders, albeit limited insights, but does not provide visibility of the composite whole. This analysis method seeks to redress this deficiency. However, the study is based upon historical data and, as such, the analysis is subject to the limitations inherent within the data collection mechanism. This analysis method is not an idealised solution for the treatment of change order data but, given that similar data will be generated by most systems, it presents an opportunity to gain some insights into the *total* delivery process. The data was treated in such away as to give a view of the cumulative effects of change orders and thus insights into the total impact of contract issue design changes on construction projects. As was stated earlier, it has been suggested that not all contract issue design changes constitute design development, or can be viewed as an intrinsic component in the evolution of a design, in fact, a significant proportion of them can be considered to be waste / inefficiencies within the design process.

In addition to the change order data sheets, information regarding how the design teams had split the designs into manageable work packages was collected. The information included a description of each work package, the work package code, the cost of the work package and the dates when construction work commenced and ended on site. Typically construction projects are managed in terms of work packages, which may be aligned to specific building elements, specific contractors or some combination of these. Even after the award of a contract, the management contractor may decide to merge or segregate work packages to facilitate better project management. In terms of design management, the proportion of change orders that impinge on more than one work package can be taken as some measure of the success in achieving an appropriate division. Purely as a device to aid presentation, in all subsequent analysis the cost of any change order that affects more than one work package (and does not have separate data for each) will be shared equally between them. Interestingly, Suh (1990) stresses the need to 'decouple' a design such that a particular aspect of the solution only caters for one functional requirement. If a change is then made to a particular functional requirement the change will only impinge upon one aspect of the design. A profile of each project was also compiled covering issues such as the type of project, approximate size of the building, budget, type of contract, length of project, level of innovation and compliance to programme.

The data for each case study was retrieved in the form of hard copy data sheets which were manually entered into a spreadsheet. The data was then analysed using a number of graphical techniques to address the objectives of this study. The following stacked bar graphs, simple bar graphs and line graphs were produced:

- *cost* vs. *reason category*, with the cost split proportionally by *originator*
- *cost* vs. *work package*, with the cost split proportionally by *originator*
- *cost* vs. *work package*, with the cost split proportionally by *reason category*
- fraction of work package cost vs. work package
- change order request count vs. work package
- cumulative cost & cumulative count vs. fractional duration (line graph)

The first study performed was the Cranfield University Library. For the purposes of making comparisons between projects, grouping and labelling data, Cranfield University Library was used as the archetype to which successive case studies were referenced. This includes assigning equivalent work packages the same numbers, using common reason categories, etc.

5.6 OVERVIEW OF THE CASE HISTORIES

For this study four case histories were initially investigated. These are the Cranfield University Library, Heathrow Cargo Warehouse, Marks & Spencer in Preston and Friar's Court Shopping Centre in Aylesbury. The case studies were nominated by the project's industrial partners on the basis of availability and accessibility of data. There is also a particular bias in the data towards projects that were thought to be successful projects by the stakeholders, although evidence for this is largely anecdotal. There are two main reasons for this bias. Firstly, the industrial partners are commercial organisations who are always keen to promote themselves. The results of research are often published in the public domain and so companies are careful not to compromise their professional reputations by providing poor examples of their work. Secondly, from a research perspective, it is desirable to study *good* projects, or what the industrial partners perceive as good projects, as there is little value taking *lessons learnt* from projects which it is known are far from best practice. It also provides an indication as to which end of the spectrum of the total set of construction projects are being investigated. In this particular case, as the projects are considered to be successful, there is an implication that any results regarding design efficiency are likely to be an overestimate when compared to the average construction project.

As stated the projects were selected on the basis of availability of data and a perception of success on the part of the industrial partners. No other characteristics or profile was specified to guide the choice of case studies. As this is an exploratory piece of research this was deemed an advantageous approach as it provides an opportunity to see whether the issues affecting design efficiency are generic. If a consistent project profile was investigated any findings could only credibly be claimed to be endemic to a project constituting the same, or similar, characteristics. On the issue of profiles, the traditional question when making comparisons is, “Are you comparing apples with apples?” However, it is not immediately clear how to categorise buildings. For instance, buildings can be grouped by function, e.g. offices, or by the type of construction, e.g. steel frame, glass frontage. Is a steel frame glass fronted office block more akin to a concrete frame masonry clad office, or a steel frame glass fronted library or retail area? The answer may even change depending on what stage of the *total* construction project is under consideration. However, the most important aspect of the research at this stage in the understanding of change orders is to keep a broad perspective so as not to prematurely rule out potentially important factors.

Project Team	**Cranfield University Library**	**Heathrow Cargo Warehouse**
Client	Cranfield University	Lynton/BAA
Architect	Sir Norman Foster and Partners	Geoffrey Reid
Management Contractor	Taylor Woodrow Management Contracting Ltd. (TWMC)	
Quantity Surveyor	Davis Langdon & Everest	Franklin and Andrews
Structural Engineer	Ove Arup & Partners	WSP Consulting
M+E Engineer	JR Preston	WSP Consulting
Project Team	**Marks & Spencer, Preston**	**Friar's Centre, Aylesbury**
Client	Marks & Spencer	
Architect		Stanley Bragg
Management Contractor	Taylor Woodrow Management Contracting Ltd. (TWMC)	
Quantity Surveyor		
Structural Engineer		
M+E Engineer		

Table 5.1 - The Professional Team for Each Case History

The professional team for each case history can be seen in table 5.1 and the profiles of the case studies investigated can be found in tables 5.3 and 5.4. The profiles indicate characteristics relating to the *building type* and *construction planning*. Appendix A also contains case study profile information relating to *design features* and *the construction stage*. The projects are quite diverse in nature: construction of a university library, a cargo warehouse building for an airport, a shopping centre and refurbishment of a retail unit. The projects vary in total costs from £2.6 - £22 million and have planned construction periods ranging from 6 to 28 months. The type of procurement route also differs: Cranfield University Library and Aylesbury Shopping Centre – Management Contract, Heathrow Cargo Building – JCT and Marks & Spencer Preston – Marks & Spencer Design and Construct – Version 1. The floor areas vary from 3,000m^2 - Cranfield University Library to 44,219m^2 – Aylesbury Shopping Centre. The buildings have approximately the same number of storeys 3 or 4, although all have different heights. Aylesbury Shopping Centre is 23m high and Cranfield University Library 11m. The buildings have different cladding and roof types and are all considered to be of *medium* level of innovation with regard to design and assembly techniques used. Cranfield University Library and Marks and Spencer Preston were considered to be of *low* level of innovation with regard to materials, with Heathrow Cargo Warehouse and Aylesbury Shopping Centre considered to be of medium level of innovation. All of the buildings, with the exception of Cranfield University Library had difficult access to the construction site. All of the projects had delays to their programme although these were of varying magnitudes and due to problems with different work packages. The longest delay affected the Aylesbury Shopping Centre resulting in significant cost to the programme. Aylesbury Shopping Centre also had the highest number of architect's instructions issued, 877, nearly three times as many as the next highest. Information concerning key personnel on each project and the level of staff turnover is very limited. An initial investigation into the quality and completeness of the data available revealed a large disparity between the most and least complete set of records. Table 5.2 illustrates the information fields in which data was recorded for each of the case histories. It can be seen that Cranfield University Library has a full set of data, with the Heathrow Cargo Warehouse missing just the originator of the change orders. Preston has no time and originator data, and Aylesbury only recorded cost and time information. Both the Cranfield and Heathrow case histories have a resolution of one day whereas the Aylesbury data to the nearest month. On the basis of this initial study it was decided not to progress the Aylesbury project due to a lack of data.

	Cranfield	Heathrow	Preston	Aylesbury
Who?	Yes	No	No	No
When?	Day	Day	No	Month
Why?	Yes	Yes	Yes	No
Work Package	Yes	Yes	Yes	No
Cost	Yes	Yes	Yes	Yes

Table 5.2 – The Availability of Data for Each Case History (Time is Either by Day or Month)

Building Details

Name of Building		**Cranfield University Library**	**Heathrow Cargo Building 549**
Project Type		Construction	Construction
Building Type		Public sector	Commercial for let / lease
Location		Home Counties	Heathrow Airport
Floor Area		3000 m^2	Warehouses - 4400 m^2 Offices - 2100 m^2
Height		11 m	-
No. of Storeys		3	Offices - 4
Type of Construction	Brick		
	Steel Frame	✓	✓
	Concrete Frame	In-situ concrete sub-structure and columns	
	Cladding	✓	Profiled steel
	Roof Type	Steel truss	Kalzip aluminum
	Distinctive Features		60m span trusses to warehouse. Elevated transfer vehicle

Construction Planning

Type of Contract		Management contract	JCT
Length of Phase	Planned Construction	13 months	9 months
	Pre-eng.	6 months	Steel frame components fabricated off-site during construction phase
Time of Introduction to Project of Disciplines	Structural Engineer	Same time as Architect	12 months after Architect
	Quantity Surveyor	Before Architect	10 months after Architect
	M&E Consult.	1 month after Architect	14 months after Architect
	Others		Contractor - 17 months after Architect
Approx. Balance of Work (By Value)	Off-site	45.7%	-
	On-site	54.3%	-
No. of Contractors		22 (Inc. management contractor)	-
No. of Work Packages		21	-

Table 5.3 – Case Study Profiles: Cranfield University Library and Heathrow Cargo Warehouse

Building Details

Name of Building		Marks & Spencer	Aylesbury Shopping Centre
Project Type		Refurbishment / Extension	
Building Type		Retail	Retail
Location		Preston - Lancashire	Aylesbury, Buckinghamshire
Floor Area		966m^2 - Extension 5110m^2 - Refurb.	44219m2
Height		-	23m
No. of Storeys		3	4
Type of Construction	Brick		✓
	Steel Frame	✓ (encased in concrete)	✓
	Concrete Frame		In-situ concrete sub-structure and columns to Mall Level
	Cladding	Brick / stonework front	✓
	Roof Type	Flat asphalt on concrete	Steel Suspension Structure
	Distinctive Features		

Construction Planning

Type of Contract		Marks & Spencer Design & Construct - Version 1	Management Contract
Length of Phase	Planned Construction	27 weeks	28 months
	Pre-eng.	11 weeks	12 months
Time of Introduction to Project of Disciplines	Structural Engineer	Pre-tender	At feasibility stage
	Quantity Surveyor	Pre-tender	At feasibility stage
	M&E Consult.	Pre-tender	At feasibility stage
	Others	Architect - Pre-tender	Architect at feasibility stage
Approx. Balance of Work (By Value)	Off-site	30%	£8,026,450
	On-site	70%	£13,595,550
No. of Contractors		39	52
No. of Work Packages		39	84

Table 5.4 – Case Study Profiles: Marks & Spencer Preston and Aylesbury Shopping Centre

5.7 CHANGE ORDER REQUEST RESULTS FOR CRANFIELD UNIVERSITY LIBRARY

Cranfield University Library was built in 1992. It was designed by Sir Norman Foster and Partners and nominated by the company as an example of a successful project. This project was also thought to be highly successful by the client. The project cost £4.66 million and generated a total of 302 change orders at a cost of £236,985. This gives a *change order costs / project cost ratio* of 5.1%. Eleven of the change orders had a negative cost, representing savings to the project. The highest cost of an individual change order was £10,000 (Substructure and Concrete Frame: work package 3010) with the lowest at -£24,500 (Curtain Walling: work package 4030), i.e. a cost saving of £24,500. The average cost of all change orders was £787. Figure 5.2 shows the cost distribution of all the change orders for the case study. The raw data was categorised into classes with an interval of £500. The first group starts at the largest cost saving, -£24,500, and the last group ends at the most expensive change order, £10,000. The graph clearly shows that the most common interval for the cost of change orders was £0 - £500. This interval is represented 147 times, nearly 50% of all change orders. The second most common interval is the £500 - £1000 which has a frequency of 48. Approximately 88% of change orders cost the project between £0 - £2000.

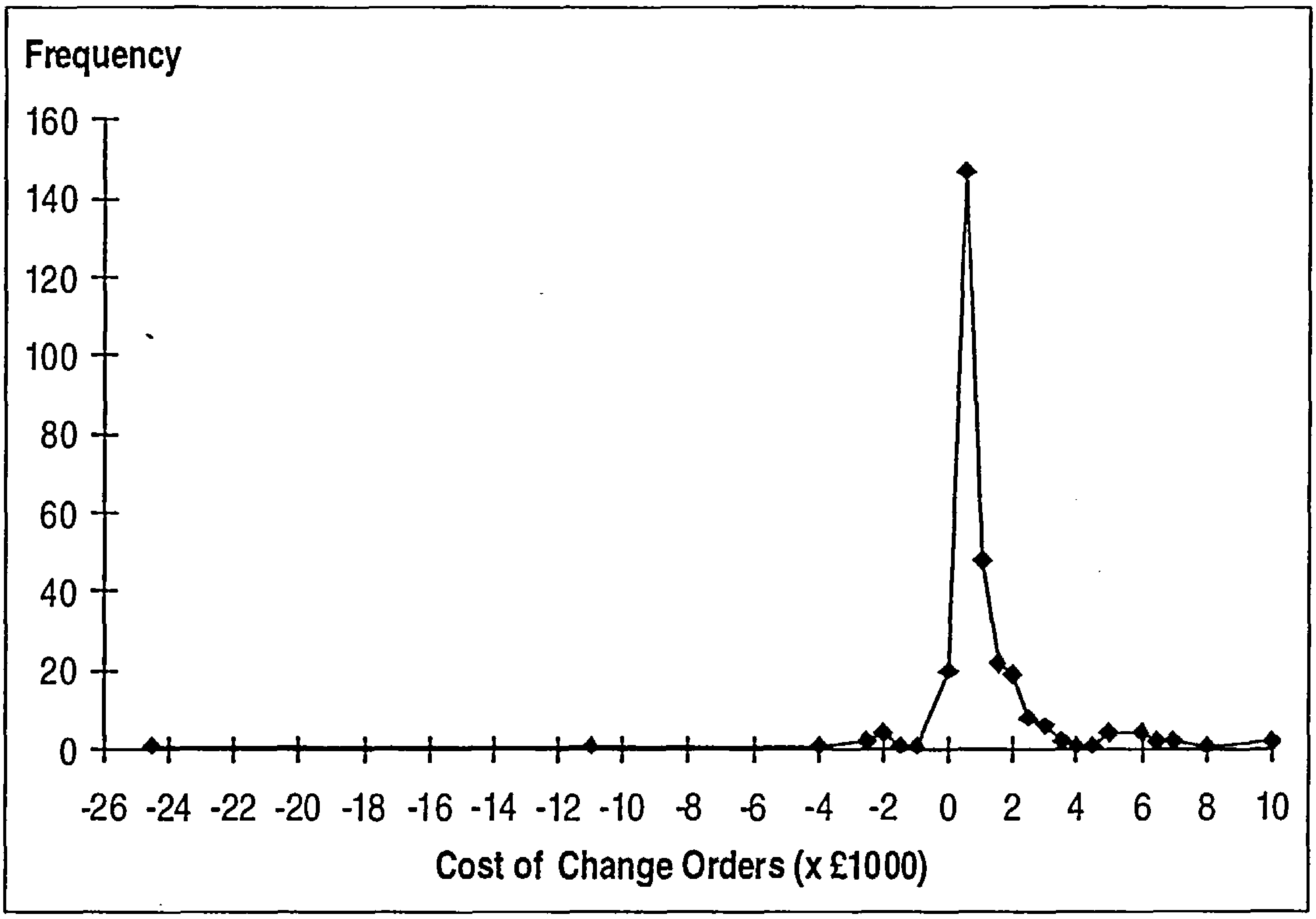


Figure 5.2 – Distribution of Change Order Costs: Cost Class Intervals of £500

Figure 5.2 can be compared with figures B.24 and B.24b in appendix B which show the cost distribution of all change orders based on the raw data, i.e. without applying class intervals.

Cranfield University Library was organised into the nineteen work packages shown in table 5.5. Each work package has been assigned a code which will appear on graphs instead of a description. Also, note that work packages 4035 (*Revolving Door*), 4040 (*Solar Louvres*) and 5070 (*Carpets*) had no change orders raised against them. This means that, in the bar graphs that follow, the sequencing of the bars from left to right is always numeric and corresponds to reading table 5.5 from top to bottom with the omission of these work packages. Also indicated in table 5.5 is the cost of each work package and the start and end dates on site. The work package costs come from the final cost plan and the start and end dates are from the final programme.

Table 5.6 shows the number of change orders affecting each work package. It also shows the level of interference: when one change order affects more than one work package. Of the 302 change orders generated, 277 impacted just one work package. A further 17 affected 2 work packages (see table 5.6 for combinations), 7 change orders affected 3 work packages and 1 change order affected 4 work packages. In total 25 change orders affected more than one work package which amounts to approximately 8% of the total number of change orders. It is also interesting to note that the average cost of change orders affecting more than one work package is £1001, where as those that affect only one is £765.

Work Package Name	WP Number	Cost	Start	End
Prelims, Management. Fee, Staff	1000	£612,097	19/08/91	24/09/92
Substructure and Concrete Frame	3010	£443,854	19/08/91	13/12/91
Roof Steelwork and Perimeter Columns	4010	£259,993	09/12/91	16/01/92
Roofing	4020	£206,250	20/01/92	02/04/92
Curtain Walling	4030	£546,536	10/02/92	13/08/92
Revolving Door	4035	£546,536	10/02/92	13/08/92
Solar Louvres	4040	£125,205	13/07/92	20/08/92
Blockwork/Partitions	5010	£228,316	3/01/92	09/07/92
Suspended Ceilings	5020	£153,892	04/05/92	10/07/92
Architectural Metalwork	5050	£96,494	04/05/92	20/08/92
Furnishings Fit-out	5060	£303,780	11/05/92	27/08/92
Carrols and Shelving	5061	£320,169	11/05/92	27/08/92
Carpets	5070	£70,379	13/07/92	20/08/92
Electrical Services	6010	£345,833	30/03/92	13/08/92
IT/Communications	6020	£102,183	27/04/92	20/08/92
Audio/Video Equipment	6030	£62,539	27/04/92	20/08/92
Mechanical Services	7010	£555,012	09/03/92	27/08/92
Lifts	8010	£51,514	30/04/92	09/07/92
Landscaping/Drainage	9010	£145,000	13/07/92	24/09/92

Table 5.5 - Work Package Costs and Timings for Cranfield University Library

No. of Work Packages Affected	Work Package Names	Number of Occurrences
1	Various	277
2	3010 5060	1
2	3010 6010	1
2	3010 9010	1
2	4020 4010	1
2	4030 4010	3
2	4030 5061	1
2	5010 5060	2
2	5020 6010	1
2	5060 7010	1
2	6010 6020	1
2	6010 7010	2
2	6010 9010	1
2	7010 5060	1
3	4010 4030 5010	1
3	5060 6010 7010	4
3	5060 7010 9010	1
3	6010 5060 5010	1
4	4020 8010 5020 3010	1

Table 5.6 - Frequency of Change Orders Affecting One or More Work Package

The reason categories available to the originator at the time of requesting a contract issue design change are shown in table 5.7. *Other* denotes the limit of the resolution and *Empty* has been included in the analysis to allow the inclusion of partially complete records. The reason categories are high level with only a limited degree of specificity.

They *do not* identify the root causes of change orders but rather diagnose the symptoms. It should be noted that the underlying rationale behind the change order request system is for contractual purposes rather than as a project management tool for process improvement. The system exists to facilitate design evolution, to reflect the changing needs of the client, allow for errors in design information and unforeseen restrictions / conditions. The change order request system is a means of authorising compensation to contractors and subcontractors for errors in design information. This is especially apparent when information is omitted in the tender documents and the contractor's bid did not take into account the omission. Hence, the reason categories used provide insights into the symptoms of change orders rather than root causes.

Figure 5.3 shows a stacked bar graph showing change order *costs* vs. *reason category*, with the cost split proportionally by *originator.* This graph provides insights into which causes of change orders are costing projects the most money and how this relates to the originator of the design change.

Label	Description	Explanation
A	Improvement Resulting from Subcontract Design	Subcontractor identifies ways to save money / time or add value to the product - which may cost the project in some way.
B	Cost Saving Measures	Need to reduce costs, cheaper option sought.
C	New Information on Existing Site Conditions	New information regarding site found, perhaps from a survey or work on site.
D	Employer has Changed His Requirements	Client requires a design change because his needs have changed. Reasons range from commercial constraints – fluctuations in market to change in taste.
E	Forced Upon Project from Shop Drawing Co-ordination	Drawing co-ordination identified an inconsistency / infeasible solution.
F	Programme Advantage or Assurance	Design change will shorten the programme in some way or reduce risk.
G	Statutory Body Requirement Came to Light since Placing of Trade Contract	Statutory body requirement identified which impacts the design of the product.
H	Public Utility Requirement Came to Light since Placing of Trade Contract	Public utility requirement identified which impacts the design of the product.
I	Designers Omission in Tender Documents	Important information omitted from the tender documents.
J	Co-ordination Defects in Tender Documents	Errors in tender documents due to poor co-ordination of information.
K	Management Contractor Omission from Packaging	Important information omitted by management contractor when creating work packages.
DD	Design Development	Design development by the design team to improve the product in some way that adds value to the scheme.
L	Other	When a change order does not fall into one of the categories above.
Empty	Not Recorded	Put in during the analysis to facilitate the processing of partially complete records.

Table 5.7 – Reason Categories Available for Cranfield University Library Case Study

This can indicate the extent to which change orders are being used to enhance the design through design evolution and conversely those which are due to inefficiencies in the design decisions making process, be they co-ordination problems, due to limited knowledge of a particular domain, errors in tender documents or other related issues. In this instance the graph shows that the most important reason categories in terms of cost are E (*Forced Upon Project from Shop Drawing Co-ordination*), I (*Designers Omission in Tender Documents*) and L (*Other*). Reason categories E and I represent shortcomings in the total design process as the design team has a large degree of control over these issues. Reason category L represents the limitations of the change order request system.

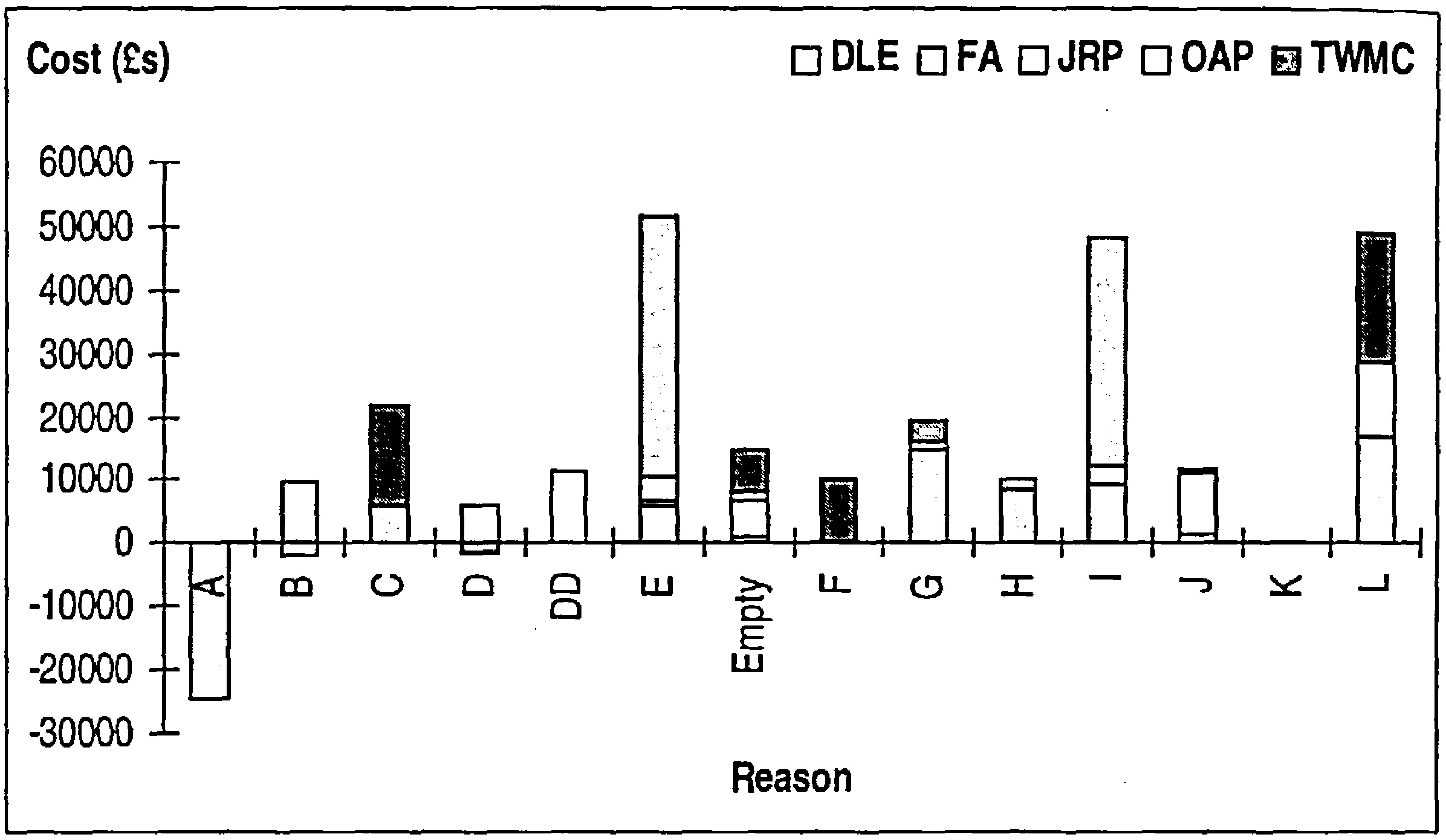


Figure 5.3 – Change Order Costs: Reason & Originator

It is the second most important reason category in terms of cost and yet reveals no information about the cause of these change orders. This is significant from a process management perspective as nearly 21% of the total cost of change orders fall into reason categories that are not represented in the system. Figure 5.3 also shows that 86% of the cost of change orders were originated by the architectural practice and project management contractor: Sir Norman Foster & Partners – 29% and Taylor Woodrow Management Contracting – 57%. These figures are artificially high as in some instances a subcontractor, for example, suggested the design change, however, the change order was completed / processed by either the architect or project manager. The cost savings achieved to the project in reason category A (*Improvement Resulting from Subcontract Design*) shows an example of this phenomenon.

It was deemed that the following reason categories relate to process issues, or are in the direct control of the design team: E *(Forced on Upon Project by Shop Drawing Co-ordination)*, I *(Designers' Omission in Tender Documents)*, J *(Co-ordination Defects in Tender Documents) and* K *(Management Contractor Omission from Packaging)*. Table 5.8 shows the total change order costs for each reason category and table 5.9 the percentage of change order costs related to process issues. From this table it can be seen that 64.9%[1] of the cost of change orders relate to process issues.

Originator's Reason Category	Cost of Change Orders (£s)
A	-24400
B	7658
C	21700
D	4420
DD	11350
E	51425
Empty	16101
f	9982
G	19500
H	10175
I	48122
J	11915
K	0
L	49037
Grand Total	236985

Table 5.8 – Total Change Order Costs for Each Reason Category

If the view is taken that the briefing process (including feasibility studies, etc) should sufficiently address issues *of Site Conditions* (C), *Statutory* (G) and *Public Body* (H) requirements prior to the contract award then 94.8% of the total change order costs relate to process issues. Other design changes can be considered to be design development to add value / reduce cost, to improve the programme, or to respond changing client's needs. That is not to say that on average 64.9% / 94.8% of the design changes studied were not necessary in the given circumstances, but they were avoidable. From the data examined only 5.2%[2] of contract issue design changes can be attributed to design development per se.

---

[1] As it is not possible to determine if change orders assigned with *Other* and *Empty* relate to categories defined as process issues their totals have been deducted from the 'Grand Total' for the purposes of calculating the percentage cost of change orders relating to process issues.

[2] That is 5.2% of the net cost, i.e. the data set included change orders with negative costs or cost savings to the project which were attributed to reason categories associated with design development. For this case study, total change order cost savings / total change order costs ≈ 11%.

Reasons	Sub Totals (£s)	Percentage of Change Order Costs Due to Process Issues
Grand Total - Other - Empty	171847	
Reasons E + I + J + K	111462	64.86 %
Reasons E + I + J + K + C + G + H	162837	94.76%

Table 5.9 – Percentage of Change Order Costs Due to Process Issues

A similar graph to figure 5.3 was produced showing change order *cost* vs. *work package* with the cost split proportionally by the *originator* (see figure 5.4). This provides a clear indication as to which work packages were generating the largest cost to the project, or where savings were made. It also shows which companies are originating the request for design changes on each work package. The most important work packages in terms of absolute costs are 7010 and 5010 (Mechanical Services and Blockwork / Partitions) which account for 30% and 15% of the total cost of change orders, respectively. The large negative cost in work package 4030 (Curtain Walling) was mostly due to a decision not to use Okalux glass due to perceived technical limitations for the application, but the change order was assigned to category A (Improvement Resulting from Subcontract Design).

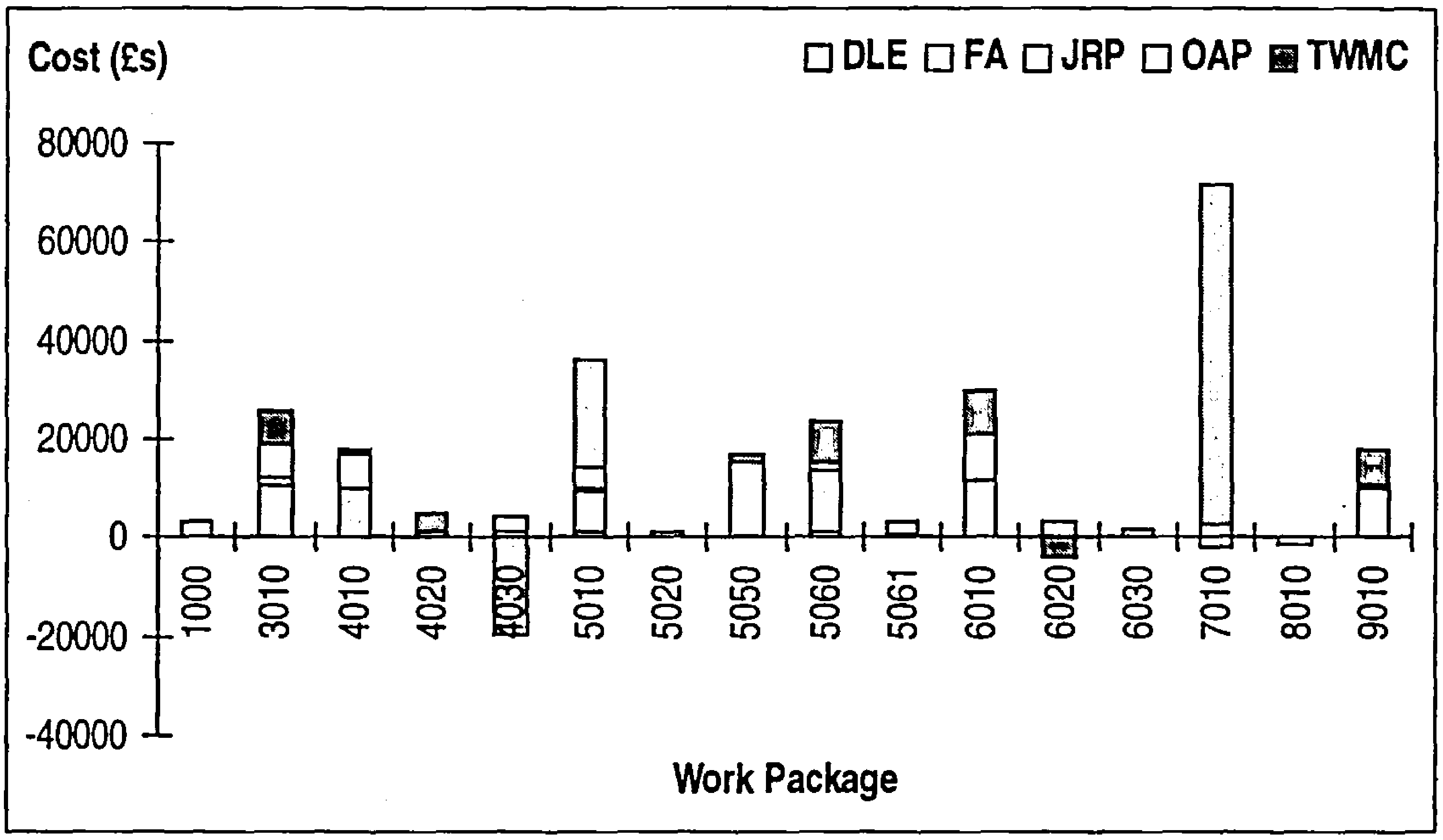


Figure 5.4 – Change Order Costs: Work Package & Originator

The final graph concerning absolute costs, *work package vs. reason category*, is shown in figure 5.5. This depicts the absolute cost of change orders affecting each work package with the cost split proportionally by reason category. This graph indicates that multiple reason categories impact the majority of work packages. *Other* has the highest incidence in terms of the number of work packages it affects, in total 15 of the 16 work packages are affected. Interestingly, the reason category with the second highest incidence is I *(Designer's Omission in the Tender Documents)*. This reason category affects 12 of the work packages with 1000 (Prelims., Management Fees, Staff Costs (TWMC)), 5061 (Carrols and Shelving), 6030 (Audio/Video Equipment) and 8010 (Lifts) avoiding change orders. That is 12 of the 16 work packages had omissions in the tender documents which required contract issue design changes to rectify. Referring back to Figure 5.3, reason category I was ranked third highest with a significant cost to the project, approximately £48,000. There is certainly a lesson here in the importance of creating better quality tender documents in the first instance to avoid costly changes later in the process. Comparing figures 5.6 and 5.7 with figures 5.3 and 5.4 respectively indicates the cost to number ratio of change orders. For example, a reason category, or work package, could be affected by a large number of low cost change orders or by a small number of high cost change orders.

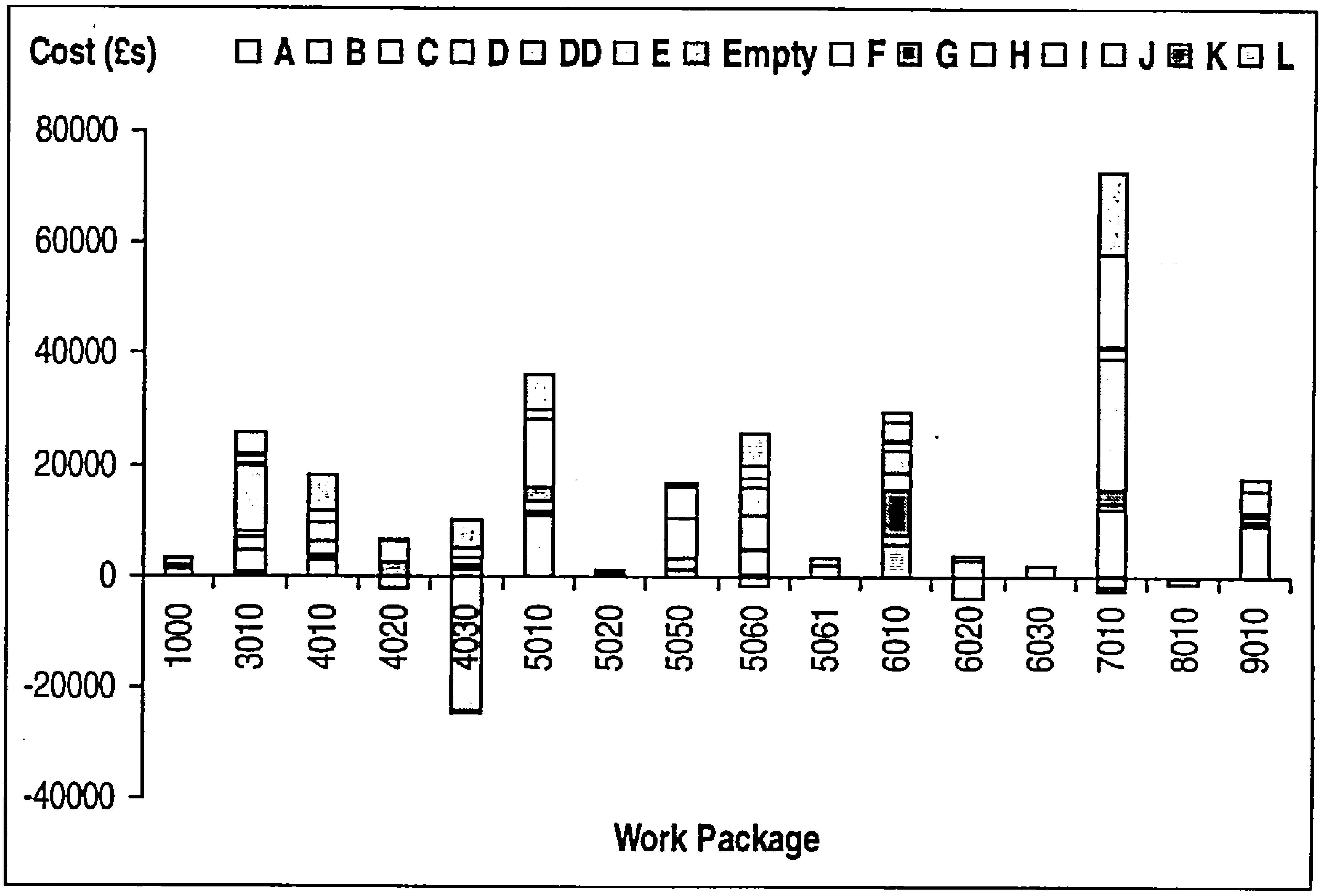


Figure 5.5 – Change Order Costs: Work Package & Reason

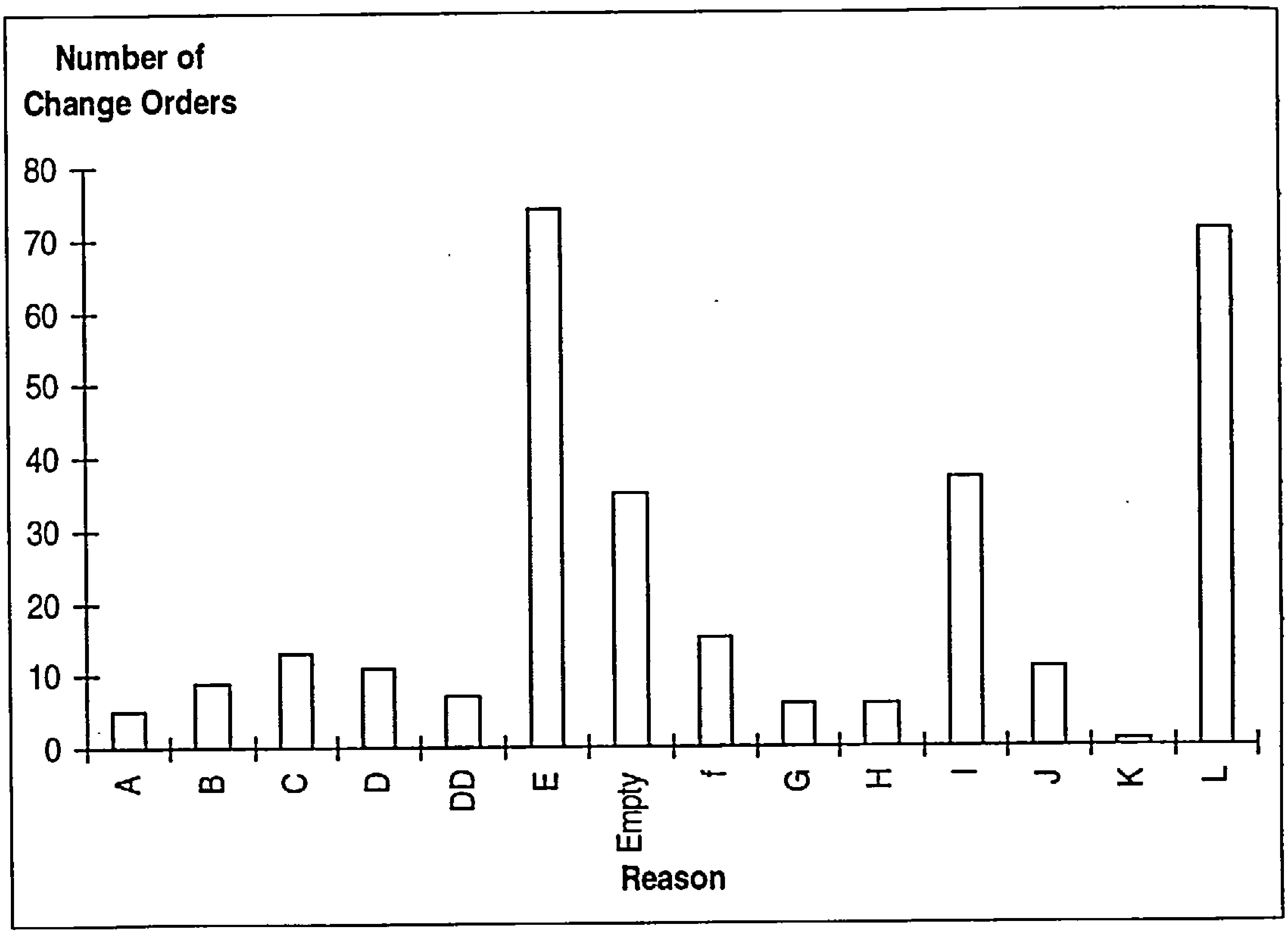


Figure 5.6 – Number of Change Orders Specifying Each Reason Category

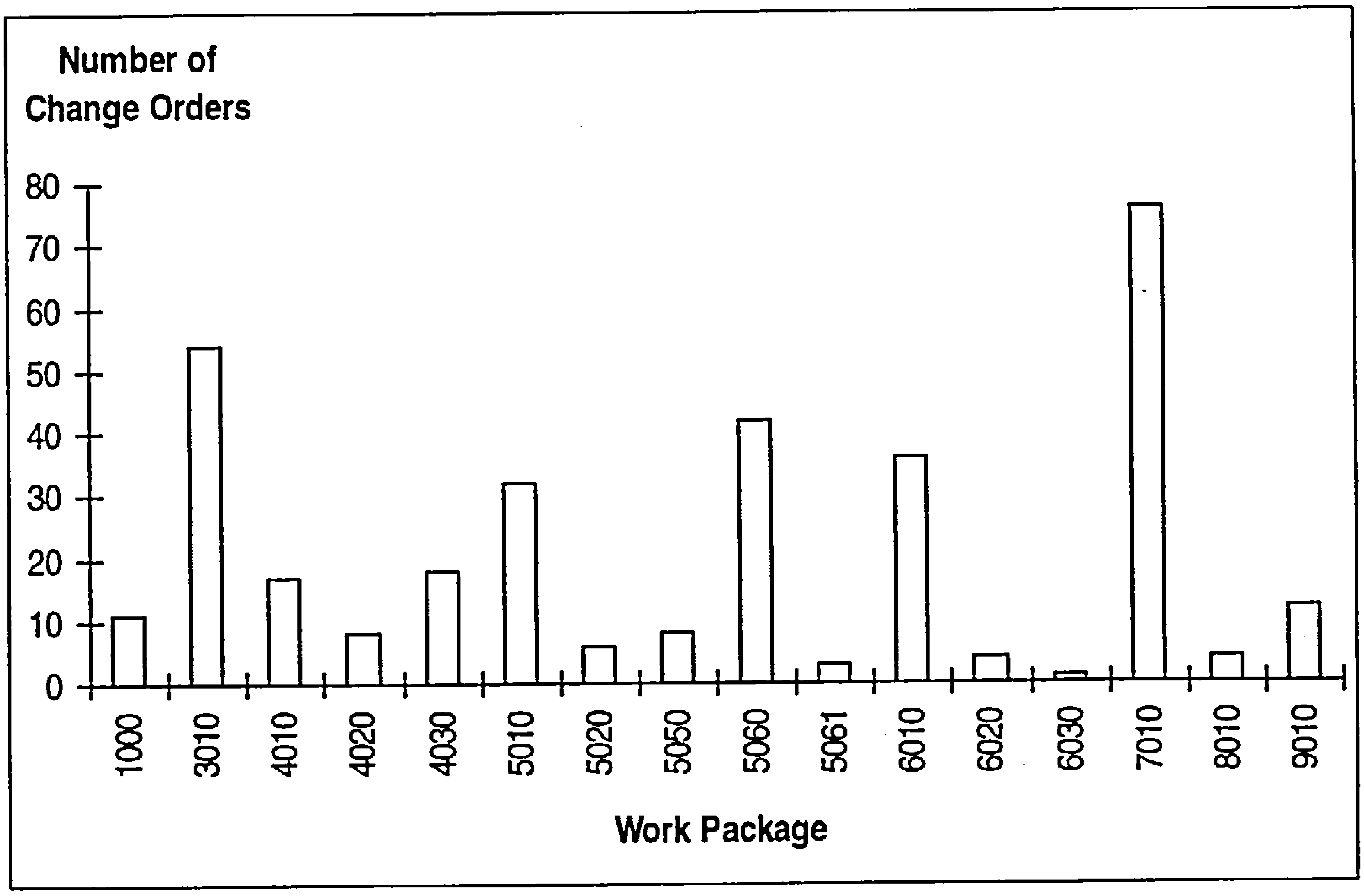


Figure 5.7 – Number of Change Orders Affecting Each Work Package

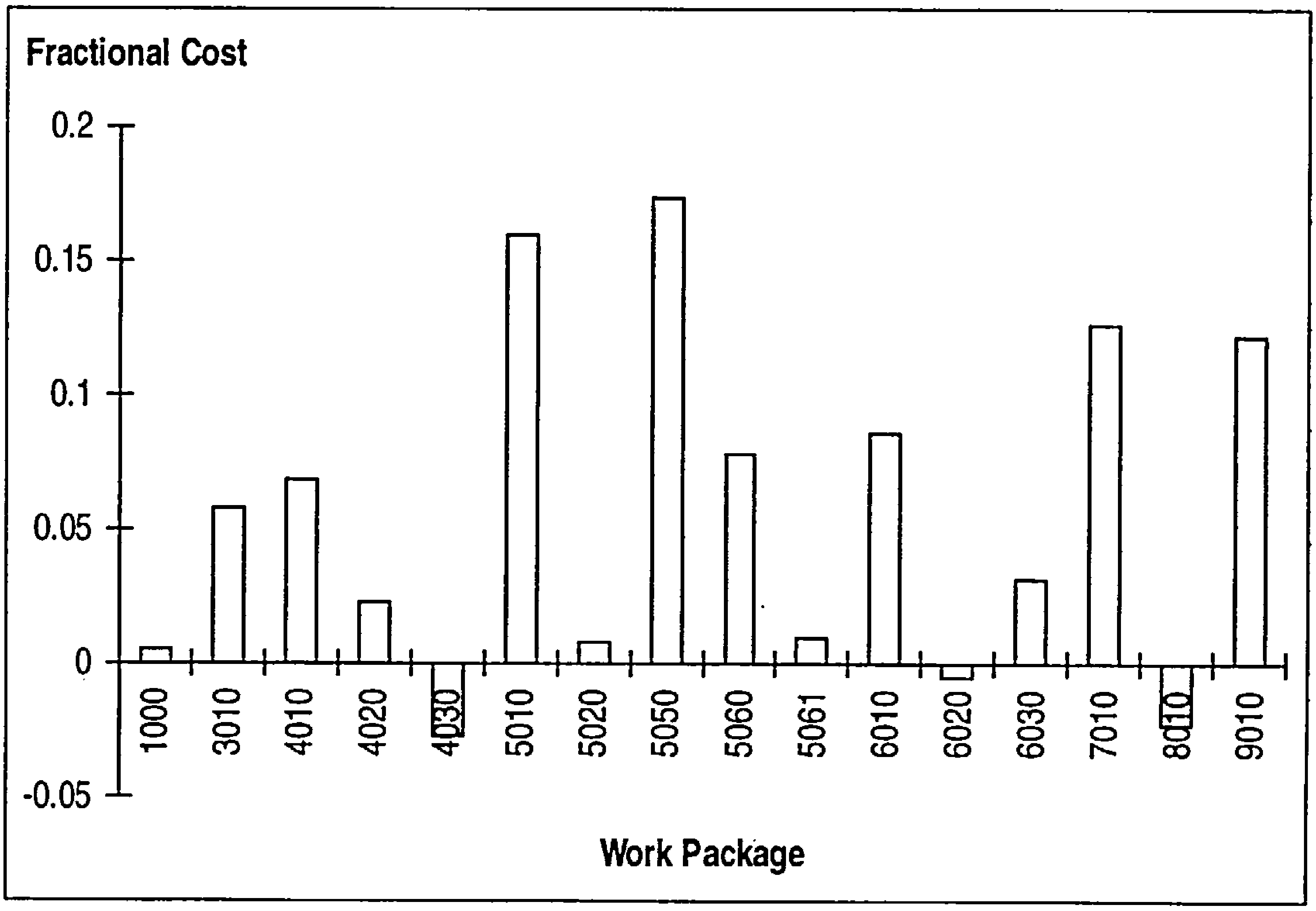


Figure 5.8 – Fractional Cost of Change Orders for Each Work Package

Taking the total cost of change orders affecting each work package and dividing by the work package costs (outlined in table 5.5) for a particular work packge, provides an alternative way of assessing the impact of change orders. Figure 5.8 shows the fractional cost of change orders affecting each work package. It can be seen that the order of importance for individual work packages has changed with the most costly now being 5050 (Architectural Metalwork) and 5010 (Blockwork and Partitions). Work package 7010 (Mechanical Services) remains significant and 9010 (Landscape / Drainage) becomes more prominent. Figure 5.8 can be compared with figure 5.5 to assess the differences between absolute and fractional costs.

Finally, it is informative to look at *when* the change orders were raised. In view of the fact that the project schedule demands different activities at different times in order to facilitate the co-ordination of work, it is important to use a relative rather than a calendar date in this analysis. For convenience, the actual start and end dates defined in table 5.5 were defined as zero and one (which are represented by vertical dotted lines on the x-axes in figure 5.9 and successive cumulative cost and count graphs), and the change order date normalised to this scale. That is, zero and one represent the start and end dates of that particular work package on site. This means that, although zero and one on the x-axis will represent a different number of days for each work package, what is of interest is the way in which the cost builds up over the duration of the work package rather than over time specifically. This allows a comparison of the cumulative effects of change orders for different work packages within a project and similar work packages across projects.

Figures 5.9 – 5.13 contain examples of the cumulative time plots for interesting work packages against which one or more change orders were raised. The graphs are shown with a common horizontal scale to facilitate comparisons between work packages. In these figures, the horizontal axis, *fractional duration*, represents normalised time, whilst the vertical axis on the right hand side is the cumulative sum of the number of change orders raised for the specified work package. A vertical step will occur in the trace for *cumulative count* when more than one change order was raised on the same day. The second vertical axis, which appears on the left of the graph, corresponds to the *cumulative cost* trace, and shows the accompanying cost information (in absolute terms, rather than normalised to the work package cost). A full set of these graphs can be found in appendix B.

Figure 5.9 shows the occurrence of change orders for work package 3010 (Substructure and Concrete Frame). This work package is significant in that it had the second largest number of change orders raised against it and ranks as the fourth most expensive work package in terms of the absolute cost of change orders. It can be seen from the graph that contract issue design changes were made to the Substructure and Concrete Frame very soon after work began on site, and continued to be made throughout its duration.

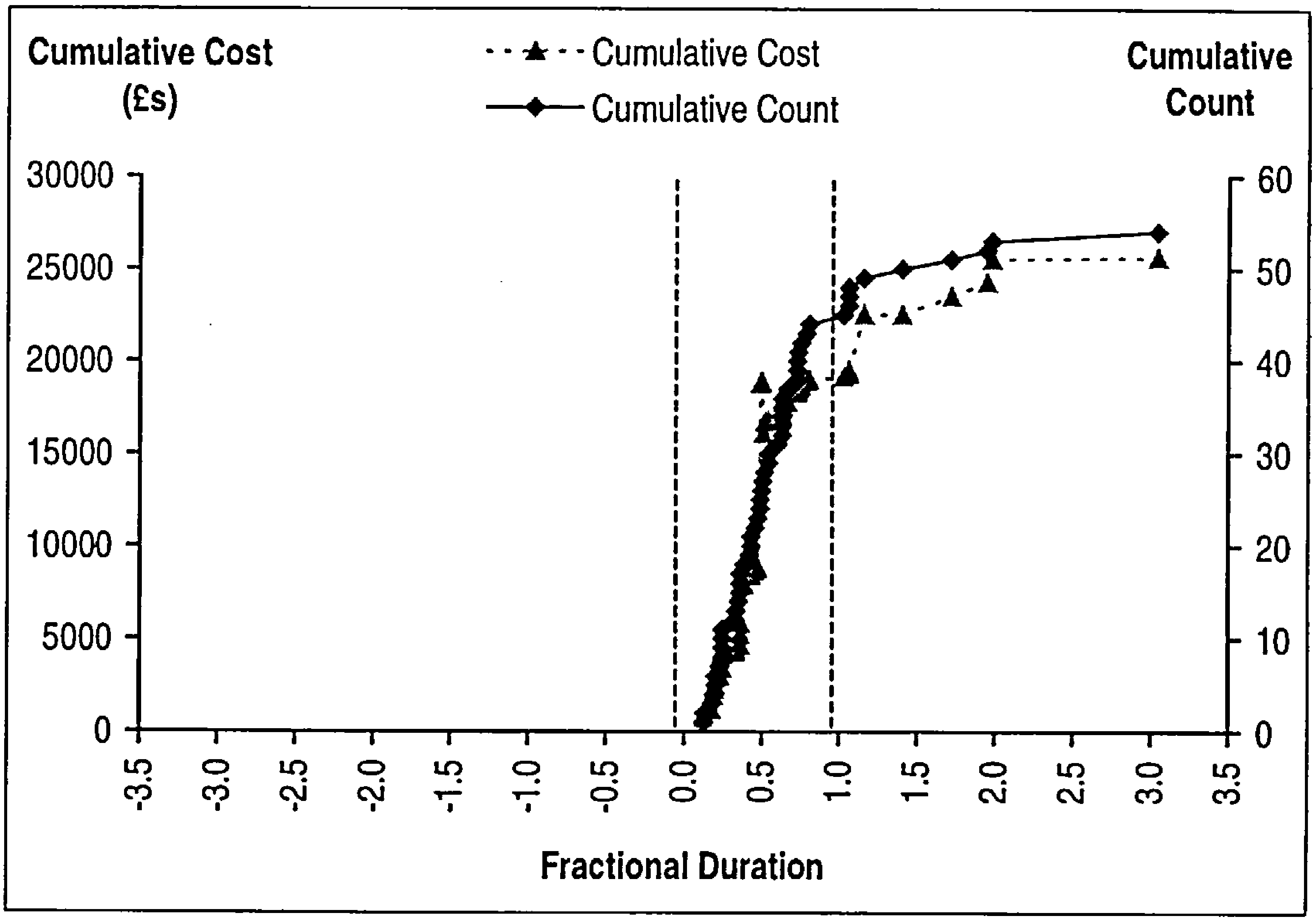


Figure 5.9 – WP 3010: Substructure and Concrete Frame

The graph displays a linear characteristic during this period. Design changes were still being made to the work package *after* work was officially completed. In this particular case, approximately 20% of change orders were raised after the end date.

Another interesting work package to consider is 5010 (Blockwork / Partitions) which is shown in figure 5.10. Blockwork / Partitions is ranked second in terms of absolute cost and fractional cost of change orders to the project. It has a similar characteristic to work package 3010 in that design changes were made throughout the entire duration on site, and beyond, but also has some made prior to work commencing on site. This is obviously a desirable characteristic as there is likely to be less impact on the project in terms of productivity losses, cost and general disruption.

Figure 5.11 shows a graph constituting considerably different characteristics to figures 5.9 and 5.10. Approximately 70% of change orders affecting the Roof Steelwork and Perimeter Columns were raised prior to work commencing on site. Again, this is a desirable characteristic and is much more pronounced than in figure 5.10. One change was made during the period on site, and four after completion. This graph shows a work package with design changes taking place over a much larger range of normalised time.

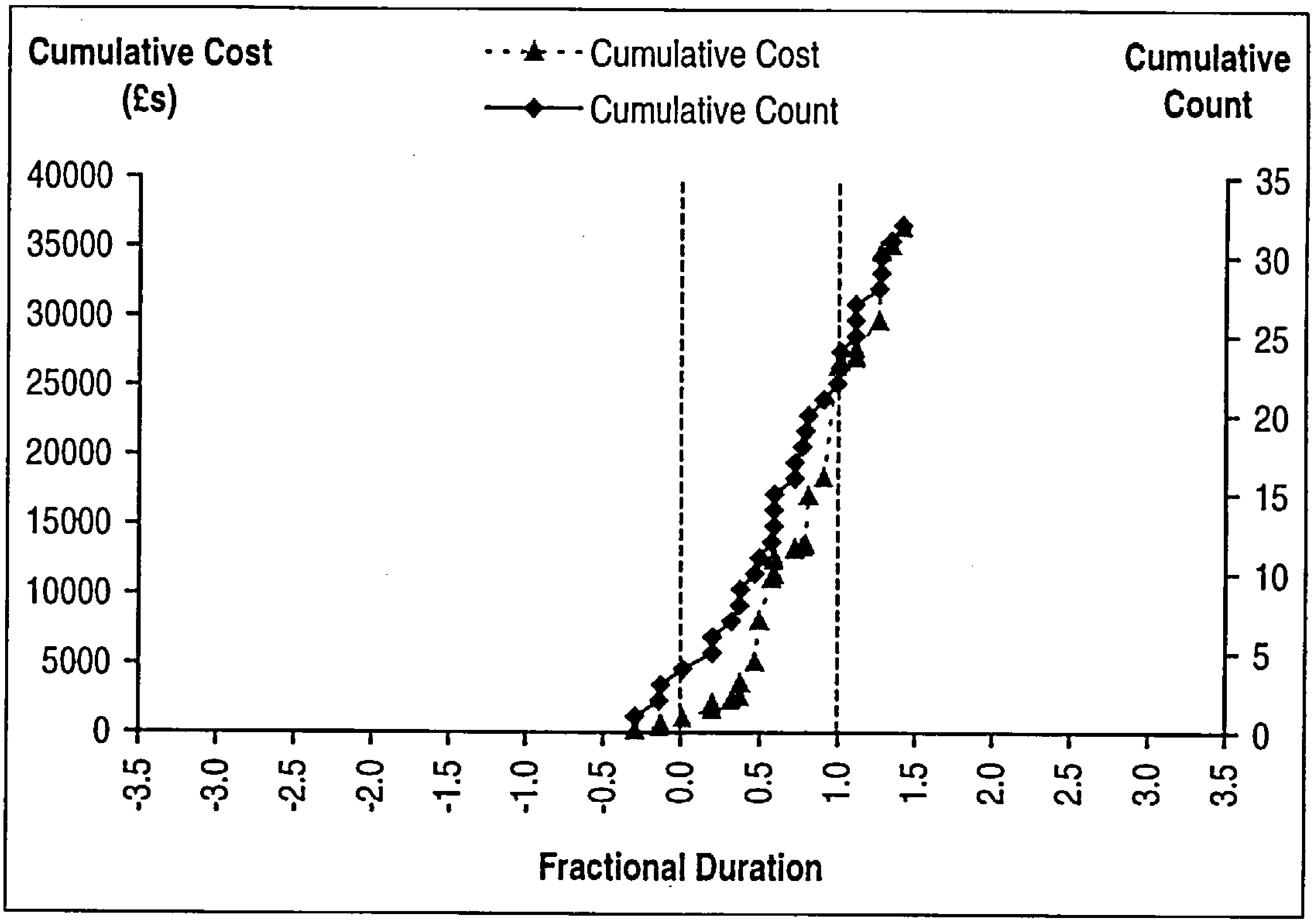


Figure 5.10 - WP 5010: Blockwork / Partitions

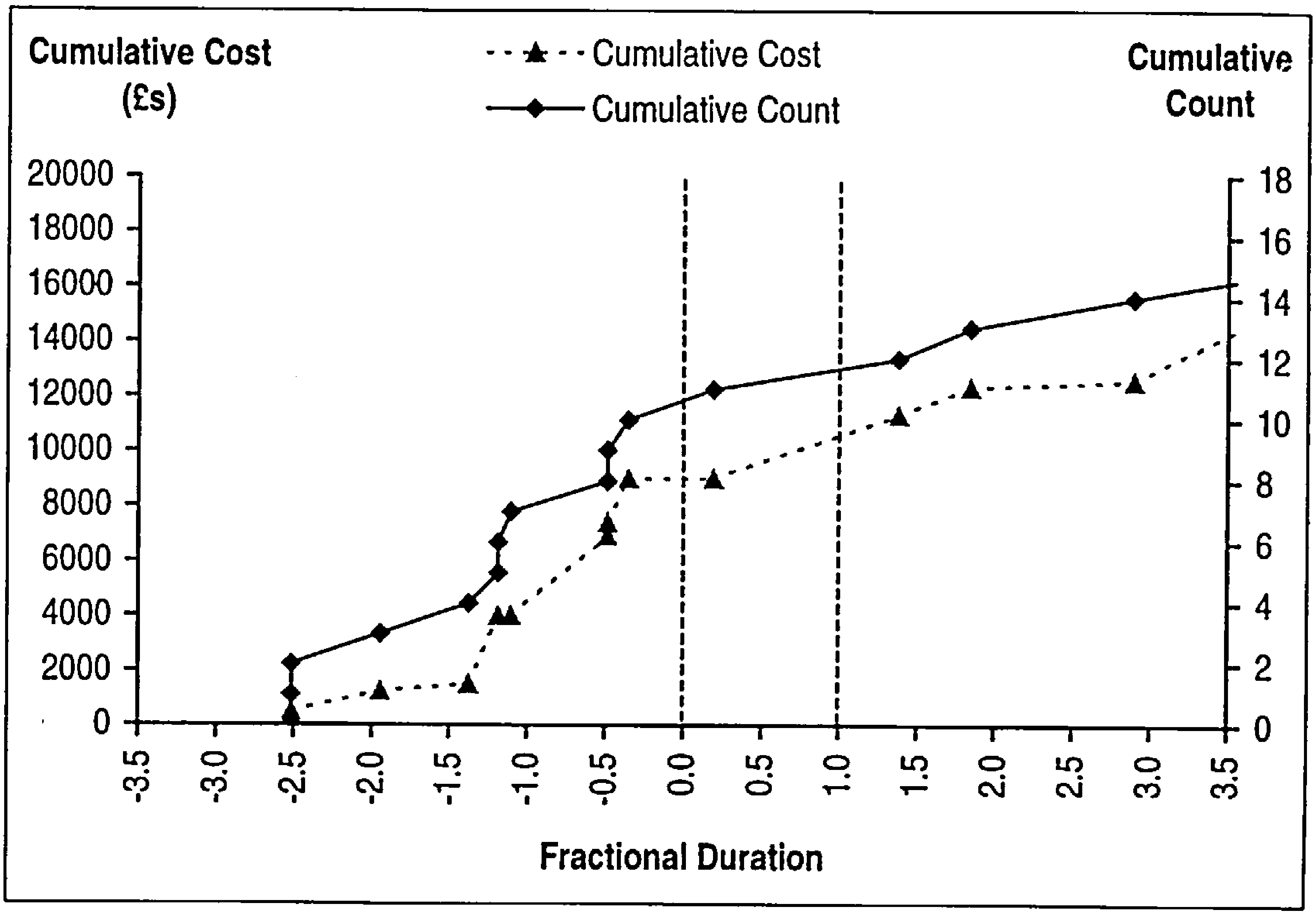


Figure 5.11 – WP 4010: Roof Steelwork and Perimeter Columns

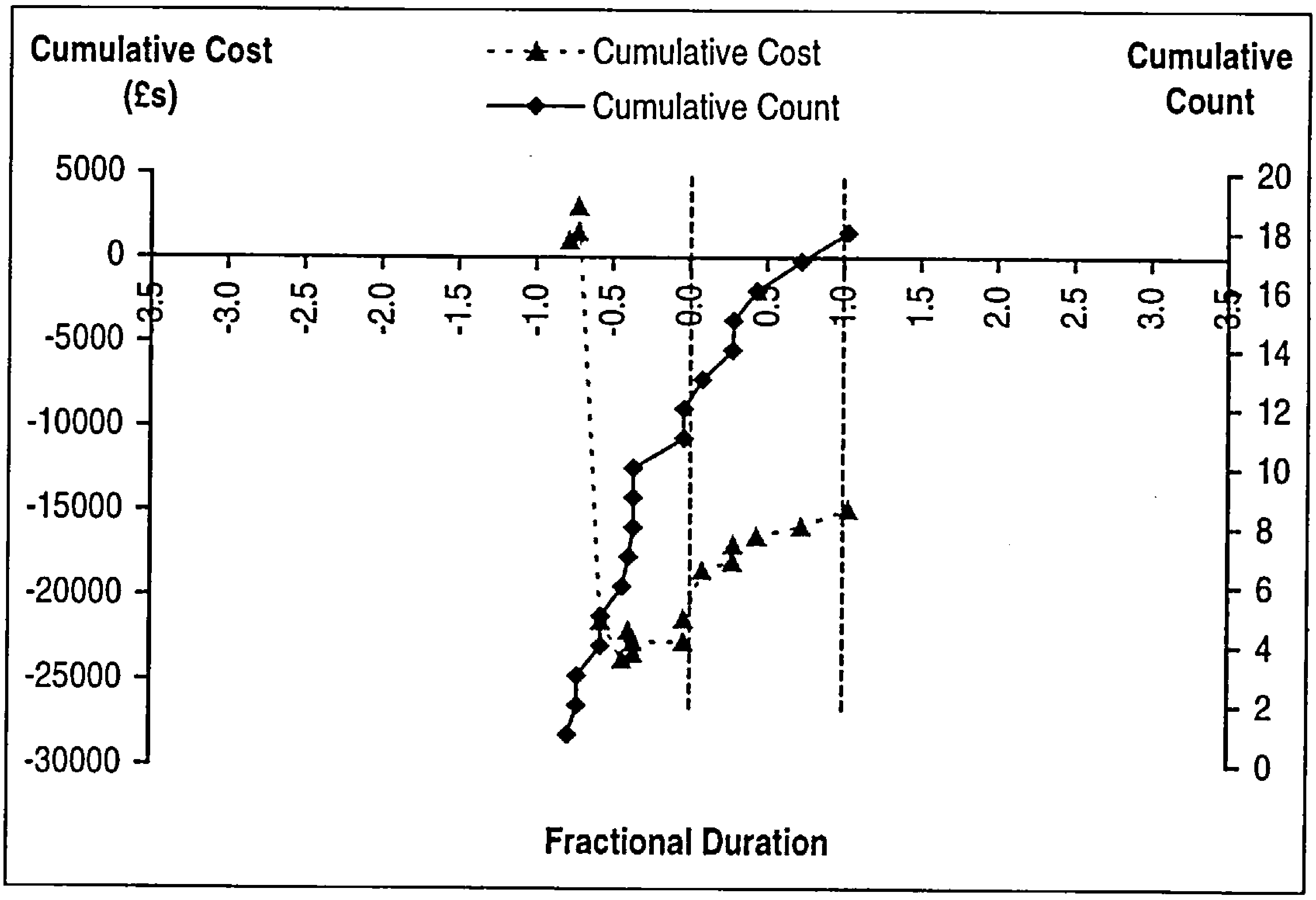


Figure 5.12 – WP 4030: Curtain Walling

Figure 5.12 shows work package 4030 (Curtain Walling). This work package is of interest because the cumulative cost curve does not track the cumulative count curve as in the previous graphs. The fourth change order affecting Curtain Walling provides a significant cost saving to the project which causes a large negative step in the cumulative cost curve, whilst the cumulative count curve has a rather linear form. The cumulative count curve then begins a more positive trend (costs to the project), although the sum of costs is much smaller than the savings.

Work package 7010 (Mechanical Services), which had the most costly change order sum in absolute terms and the largest number of design changes made to it, is shown in figure 5.13. It clearly shows that halfway through the site activity a number of change orders were raised. Also, about one quarter of the change orders were raised either before the site work started, or after it finished. The change orders raised in the second half of the period on site show a linear trend.

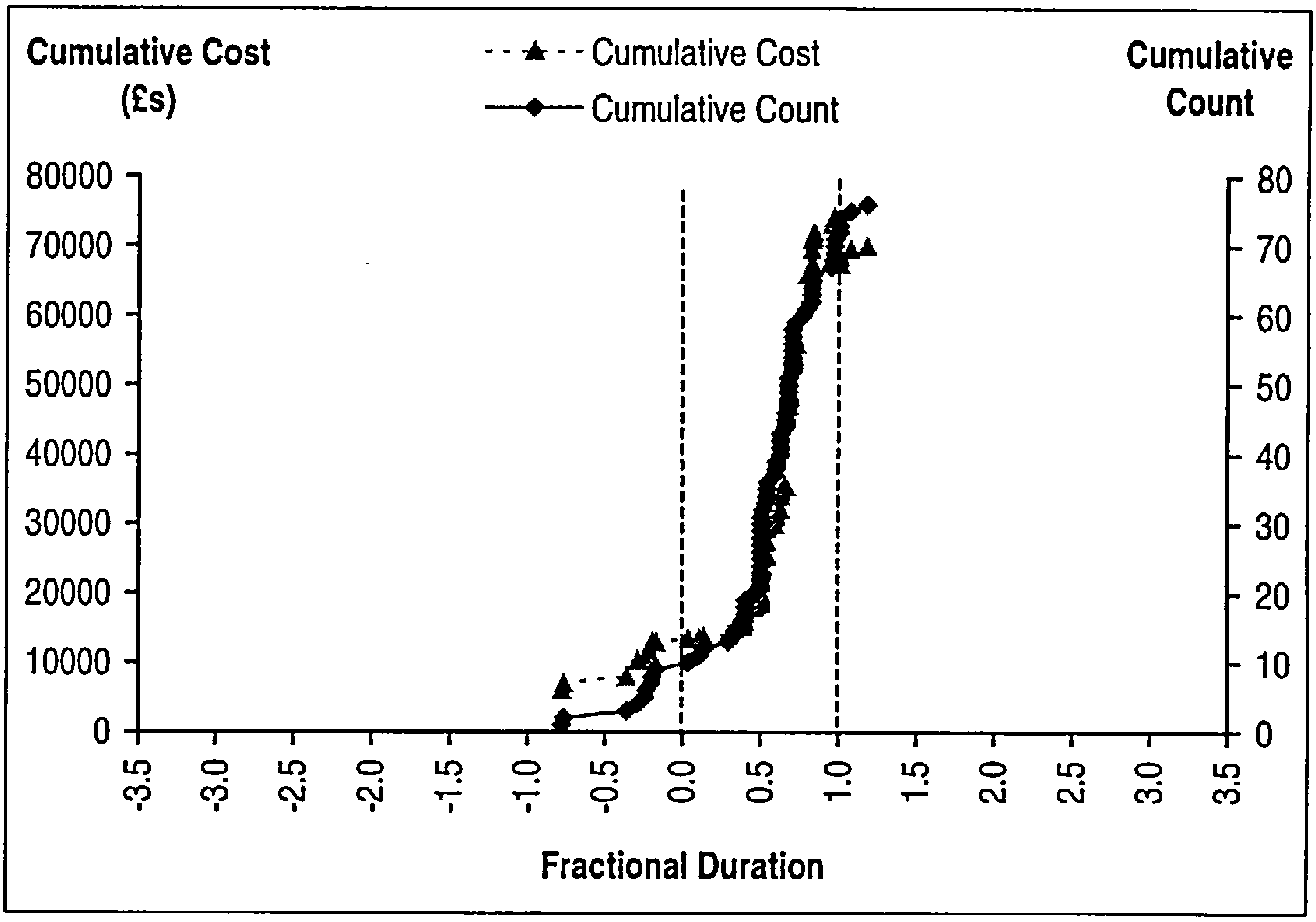


Figure 5.13 – WP 7010: Mechanical Services

5.8 CHANGE ORDER REQUEST RESULTS FOR HEATHROW CARGO WAREHOUSE

The Heathrow Cargo Warehouse was nominated by WSP Consulting Engineers as a case study for this investigation. The building was constructed in 1995 at a total cost of £2,603,873. In total 444 change orders were raised, at a cost of £197,084, which gives a *change order costs / project cost ratio* of 7.6%. Sixteen of the change orders had a negative cost, representing savings to the project, and two of the thirty work packages listed in table 5.10 had no change orders raised against them: 1000 (Preliminaries) and 10030 (Rainwater Installation). Unlike the Cranfield library project (and the Marks and Spencer Ltd Preston project considered in section 5.9), no change order raised affected multiple work packages.

The highest cost of an individual change order was £8,452 (Cladding / Coverings: work package 4025) with the lowest at -£10,500 (Mechanical Services: work package 7010-1), i.e. a cost saving of £10,500. The average cost of all change orders was £444. Figure 5.14 shows the cost distribution of all the change orders for the case study. The raw data was categorised into classes with an interval of £500.

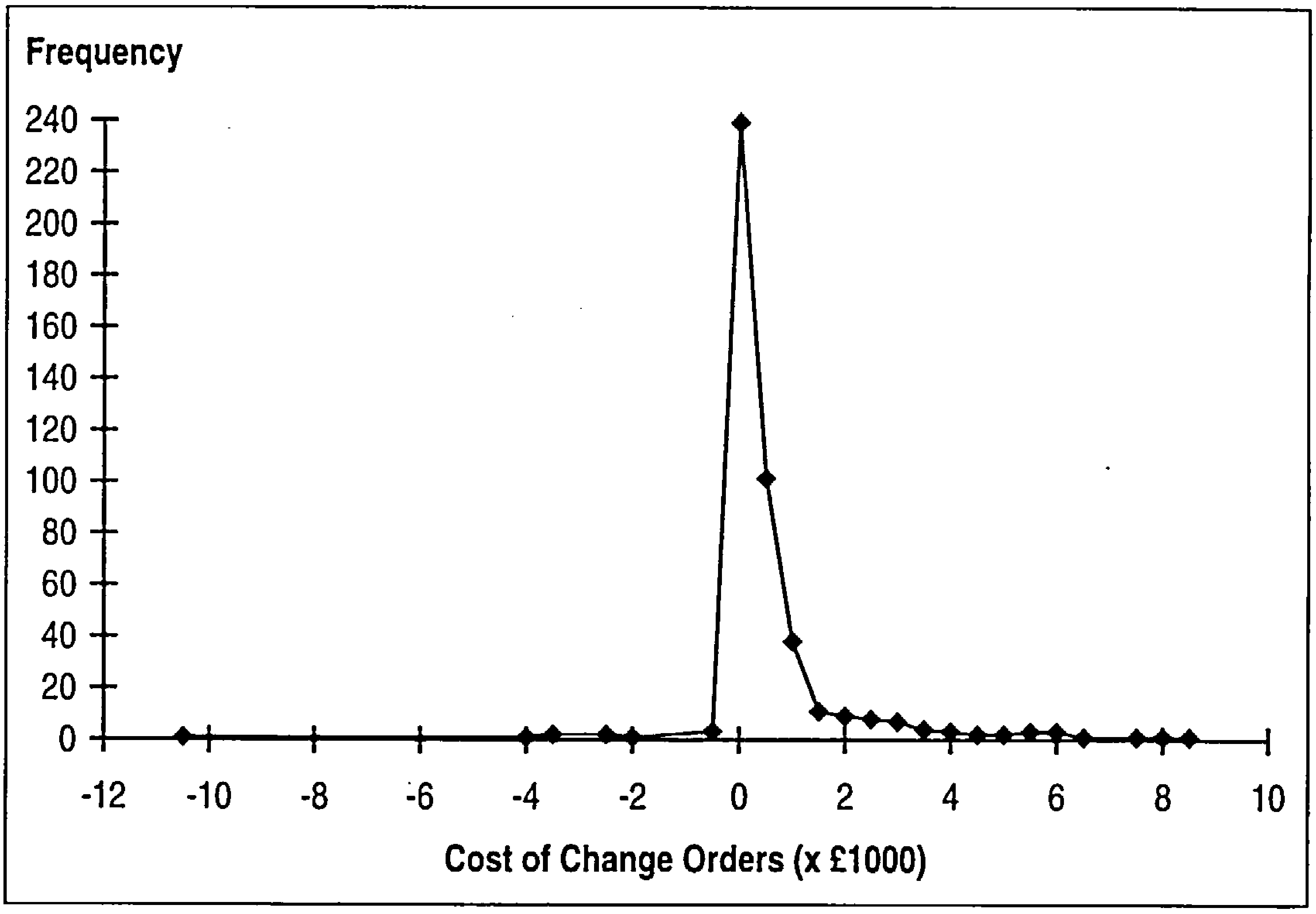


Figure 5.14 – Distribution of Change Order Costs: Cost Class Intervals of £500

The first group starts at the largest cost saving, -£10,500, and the last group ends at the most expensive change order, £8,452 (£8,500). The graph clearly shows that the most common interval for the cost of change orders was £-500 to £0. This interval is represented 239 times, nearly 54% of all change orders. This interval is mostly populated with change orders that did not cost the project any money in terms of direct cost. In total 232 of the 239 change orders in the interval have a direct cost to the project of £0. The second most common interval is the £0 - £500 which has a frequency of 101. Approximately 88% of change orders cost the project between -£500 and £1500. Figure 5.14 can be compared with figures C.31 and C.31b in appendix C which show the cost distribution of all change orders based on the raw data, i.e. without applying class intervals.

Work Package	WP Number	Start Date	End Date	WP Cost	Match
Preliminaries	1000	21/12/93	15/09/95	120000	Yes
Substructure - excav. concrete, brick / blockwork	3010-1	06/02/95	19/04/95	136625	Yes
Substructure - excav. concrete, brick / blockwork	3010-2	08/05/95	16/06/95	81975	Yes
Structural Steelwork	4010	27/03/95	16/06/95	502900	Yes
Office Roof (Roof Screed)	4020-1	15/05/95	19/05/95	9167	Yes
Office Roof	4020-2	29/05/95	06/07/95	12833	Yes
Curtain Walling	4030	15/05/95	16/06/95	73000	Yes
Brickwork / Blockwork & Plaster	5010	24/04/95	07/07/95	113100	Yes
Ceiling Finishes	5020	03/07/95	28/07/95	47900	Yes
Fitting, Furnishings	5060	07/08/95	15/09/95	21600	Yes
Building Services: Electrical	6010-1	08/05/95	21/07/95	26300	Yes
Lighting	6010-2	14/08/95	25/08/95	75200	Yes
Building Services: Mechanical	7010-1	08/05/95	30/06/95	183273	Yes
Building Services: Mechanical	7010-2	14/08/95	01/09/95	68727	Yes
Lifts	8010	19/06/95	11/08/95	44000	Yes
External Works	9010	04/09/95	15/09/95	92600	Yes
Cladding / Coverings	4025	24/04/95	16/06/95	350000	No
Doors & Ironmongery	4035-1	22/05/95	26/05/95	17000	No
Metal Doors / Hatches - Sundry Metalworks	4035-2	05/06/95	23/06/95	124900	No
Balustrading	4035-3	20/03/95	31/03/95	20600	No
Windows & Louvres	4040-1	17/04/95	12/05/95	116000	No
Solar Screens	4040-2	05/06/95	23/06/95	38000	No
Entrance Flooring & Flooring Finishes	5070	28/08/95	08/09/95	30700	No
Site Works	9020	30/01/95	17/02/95	125000	No
Staircases & Balustrades	10010-1	15/05/95	02/06/95	28320	No
Staircases & Balustrades	10010-2	26/06/95	07/07/95	18880	No
Floors - Precast Concrete	10020-1	10/04/95	03/05/95	78900	No
Raised Floors	10020-2	17/07/95	04/08/95	42900	No
Rainwater Installation	10030	24/04/95	12/05/95	3200	No
Tenant Fit-out	10040	06/02/95	15/09/95	273	No

Table 5.10 - Work Package Costs and Timings for Heathrow Cargo Warehouse

The Heathrow Cargo Warehouse project was organised into the work packages shown in table 5.10, which lists work package name and numbers, cost, and actual start and end dates on site. Where possible, the labelling of the work packages has been changed to facilitate comparison with the Cranfield Library project. The final column in the table indicates whether or not there was a work package in the Cranfield Library project that was comparable in the scope of its work. In addition, in the Heathrow Cargo Warehouse project the same work package was sometimes scheduled for more than one time period so that, in order to give a fair reflection of the change order timings, such work packages have been subdivided to reflect the programme of work. This gives rise to, for example, the work packages 6010-1 and 6010-2, both of which are comparable in scope to Cranfield work package 6010, but which were not a continuous on-site activity in the Heathrow programme.

The reason categories available to the originator are the same as those in table 5.7 for the Cranfield University Library, but with the addition of 'M' representing changes required by the tenant for fit-out *(Tenant Fit-out)*. Figure 5.15 shows the total change order costs that were raised against each of the reason categories specified by the originator. The three most costly reason categories are *L (Other)*, I *(Designers Omission in Tender Documents)* and D *(Employer has Changed His Requirements)*. In the Heathrow Cargo Warehouse project 33% of the cost of changes orders were associated with reasons not represented in the change order system. This is important from a process management perspective as a third of the change order costs are *not* represented in the system. This compares with 21% from the Cranfield University Library case study.

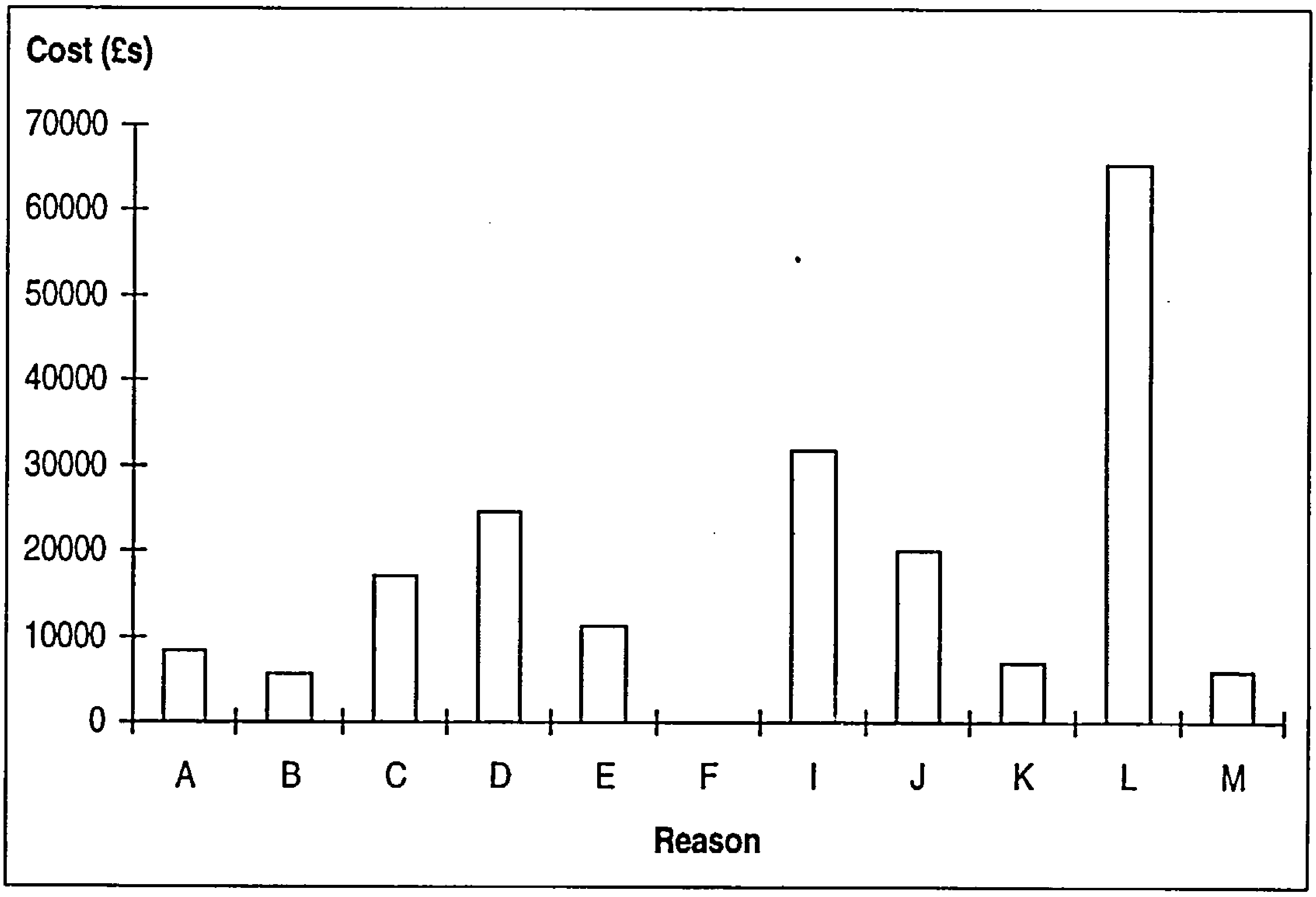


Figure 5.15 – Change Order Costs Associated With Each Reason Category

Table 5.11 indicates the change order costs associated with each reason category. Section 5.7 defines the following reasons as relating to process issues, or issues which are in the control of the design team: E *(Forced on Upon Project by Shop Drawing Co-ordination),* I *(Designers' Omission in Tender Documents),* J *(Co-ordination Defects in Tender Documents) and* K *(Management Contractor Omission from Packaging).* From table 5.12 it can be seen that 53%[3] of change order costs for the Heathrow Cargo Warehouse were because of process issues. If the view is taken that the briefing process (including feasibility studies, etc) should sufficiently address issues *of Site Conditions* (C), *Statutory* (G) and *Public Body* (H) requirements prior to the contract award then 66% of the cost of change orders can be attributed to process issues.

Originator's Reason Category	Cost of Change Orders (£s)
A	8200
B	5719
C	17070
D	24630
E	11246
F	100
I	31821
J	19911
K	6915
L	65578
M	5893
Grand Total	197084

Table 5.11 – Total Change Order Costs for Each Reason Category

Reasons	Sub Totals (£s)	Percentage of Change Order Costs Due to Process Issues
Grand Total - Other	131506	
Reasons E + I + J + K	69894	53.15%
Reasons E + I + J + K + C + G + H	86964	66.13%

Table 5.12 – Total Change Order Costs Due to Process Issues

The absolute costs of change orders raised against each work package, with the costs split proportionally by reason category, is shown in figures 5.15a and 5.15b. The graphs show that the three most costly work packages in terms of the absolute cost of change orders attributed to them are 9010 (External Works), 4025

---

[3] As it is not possible to determine if change orders assigned with *Other* relate to categories defined as process issues its total has been deducted from the 'Grand Total' for the purposes of calculating the percentage cost of change orders relating to process issues.

(Cladding / Coverings) and 7010-2 (Building Services – Mechanical). These represent 18%, 17% and 11% of the total change order costs, respectively. Six of the 30 work packages had no change order costs with a further two work packages having insignificant sums raised against them (cost saving of £30 and cost of £100). It can be seen that multiple reason categories affect most of the work packages. The reason categories affecting the most work packages are L *(Other)*, K *(Management Contractor Omission)* and I *(Designer's Omission in Tender Documents)*, which affect 20, 19 and 15 work packages respectively. Referring to figures 5.15a and 5.15b it can be seen that *Designer's Omissions in Tender Documents* had a significant cost to the project, in a similar fashion to the Cranfield University Library. This again highlights the issue of the quality of tendering documents and brings into question the efficacy of the process which generates them.

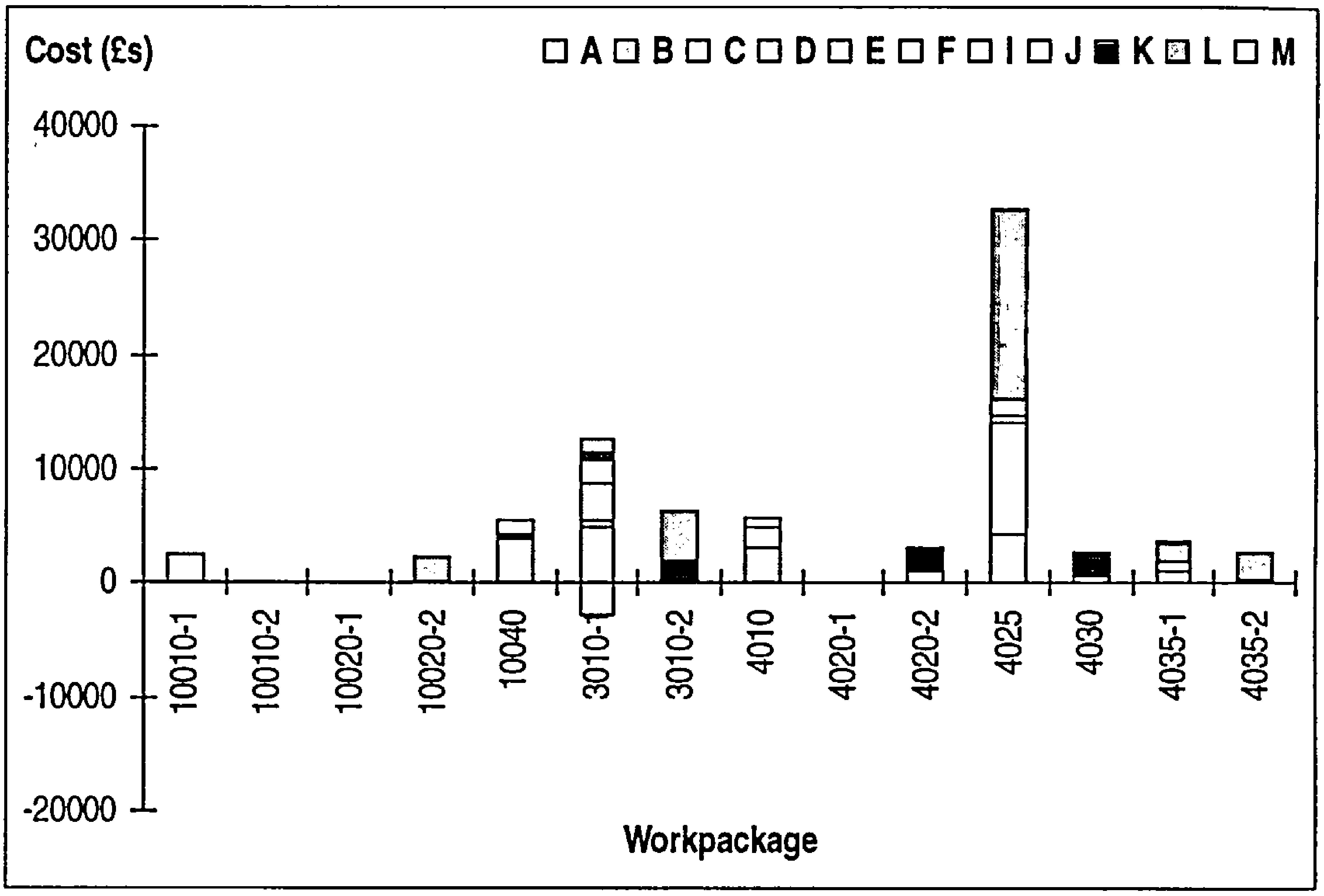


Figure 5.15a – Change Order Costs: Work Package & Reason (WP 10010-1 – WP 4035-2)

An alternative perspective on the importance of work packages in terms of change order costs is provided by figures 5.16a and 5.16b. These show the fractional cost of change orders for each work package. The fractional cost is the total cost of change orders raised against a particular work package divided by the cost of the work package (see table 5.10). The most significant work packages are 5060 (Fittings and Furnishings), 9010 (External Works) and 7010-2 (Building Services – Mechanical). Figures 5.16a and 5.16b can be compared with figures 5.15a and 5.15b. It can be seen that work package 4025 (Claddings / Coverings) is not significant at all in fractional terms comparatively speaking, however, both work packages 7010-2 and 9010 are significant in both absolute and fractional cost terms. Work package 5060 ranks third in absolute terms but first in fractional costs.

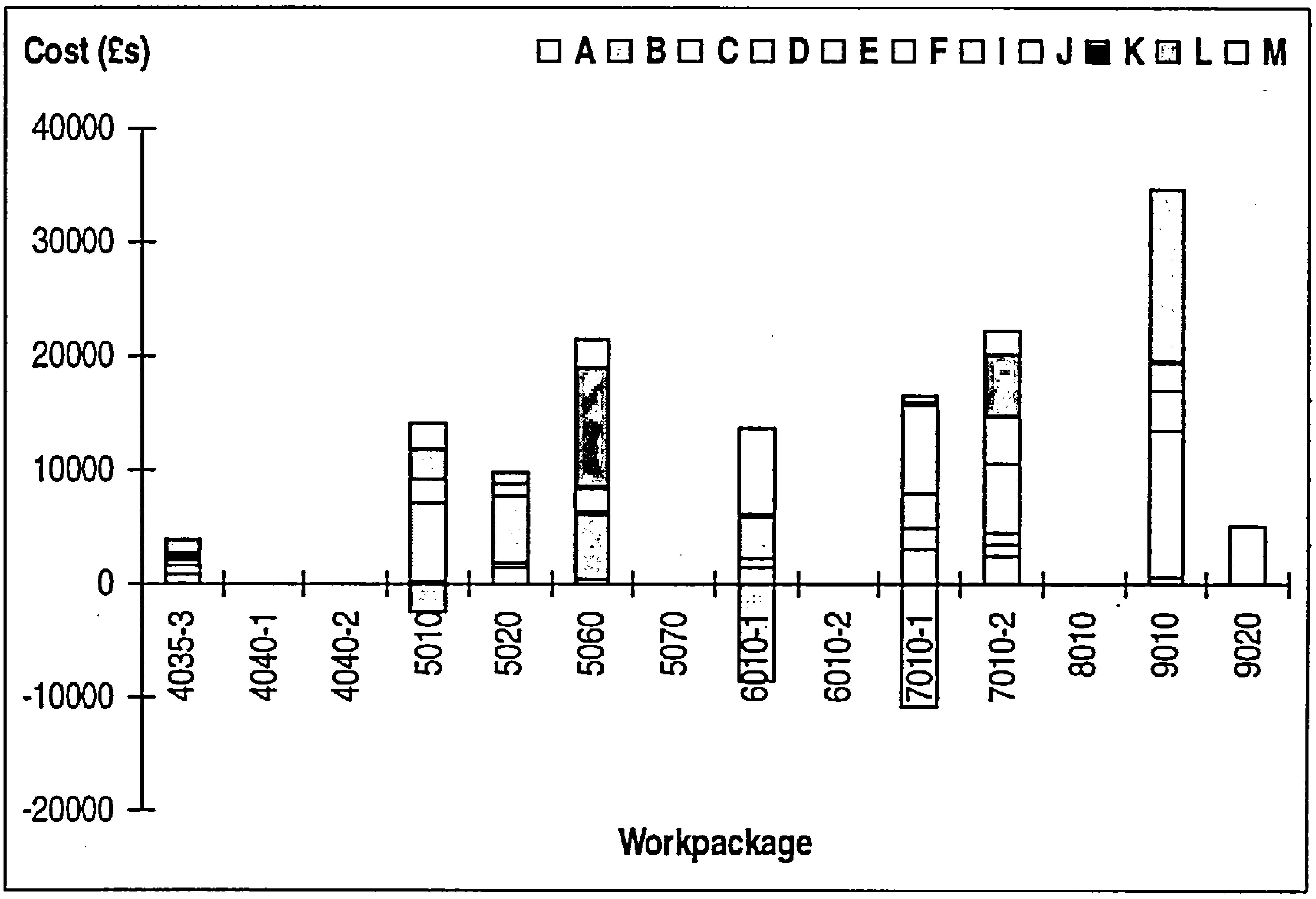


Figure 5.15b – Change Order Costs: Work Package & Reason (WP 4035-3 – WP 9020)

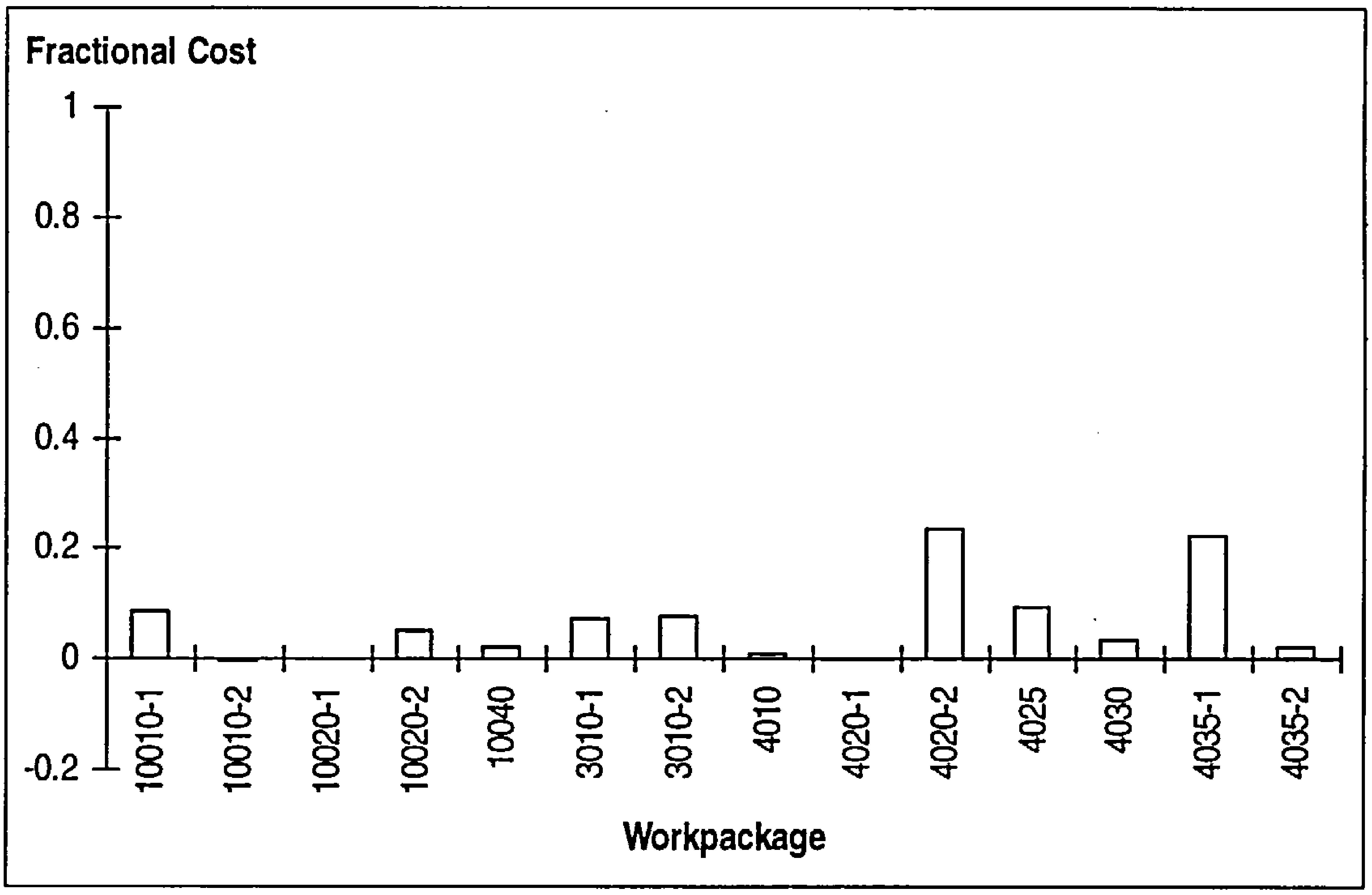


Figure 5.16a – Fractional Cost of Change Orders for Each Work Package (WP 10010-1 – WP 4035-2)

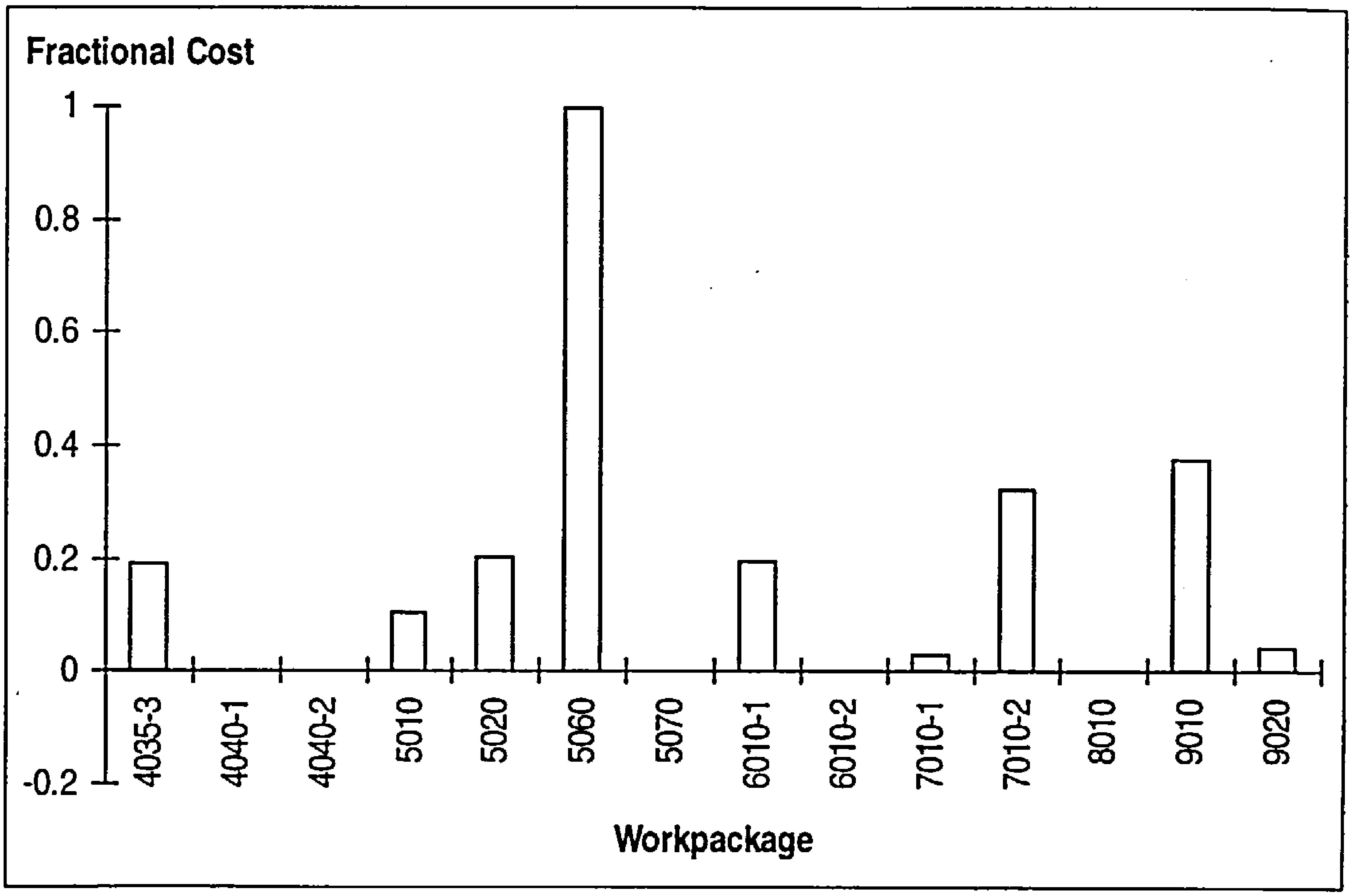


Figure 5.16b – Fractional Cost of Change Orders for Each Work Package (WP 4035-3 – WP 9020)

Comparing figures 5.17a and 5.17b with figures 5.15a and 5.15b provides insights into whether a large number of low cost or a small number of high cost change orders were raised against a particular work package. For example, work package 4025 has a relatively low number of expensive change orders affecting it. A similar comparison can be made between figure 5.15 and figure C.8 in appendix C for the reason categories.

Appendix C contains the cumulative time plot for each work package against which four or more change orders were raised, with the graphs constructed as explained in section 5.7. Note that most graphs are shown with the normalised time axis running from -3.5 to +3.5 but four of the graphs (figure C.15 - WP 4035-1 Doors and Ironmongery, figure C.17 - WP 4035-3 Balustrading, figure C.26 - WP 9010 External Works and figure C.27 - WP 9020 Site Works) are shown with a normalised time axis extending from -18 to +18 in order to accommodate the change orders that were raised against these work packages.

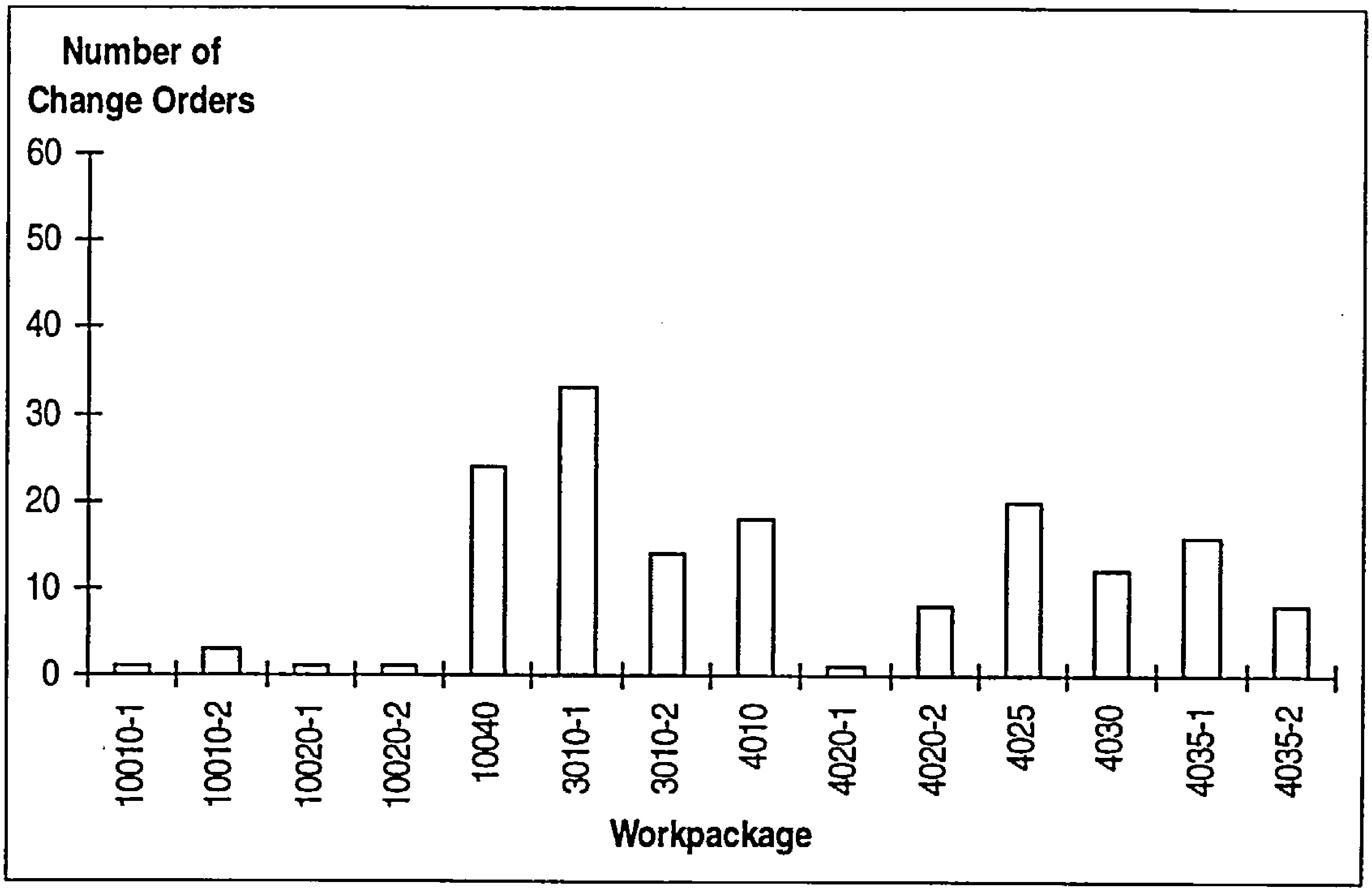


Figure 5.17a – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2)

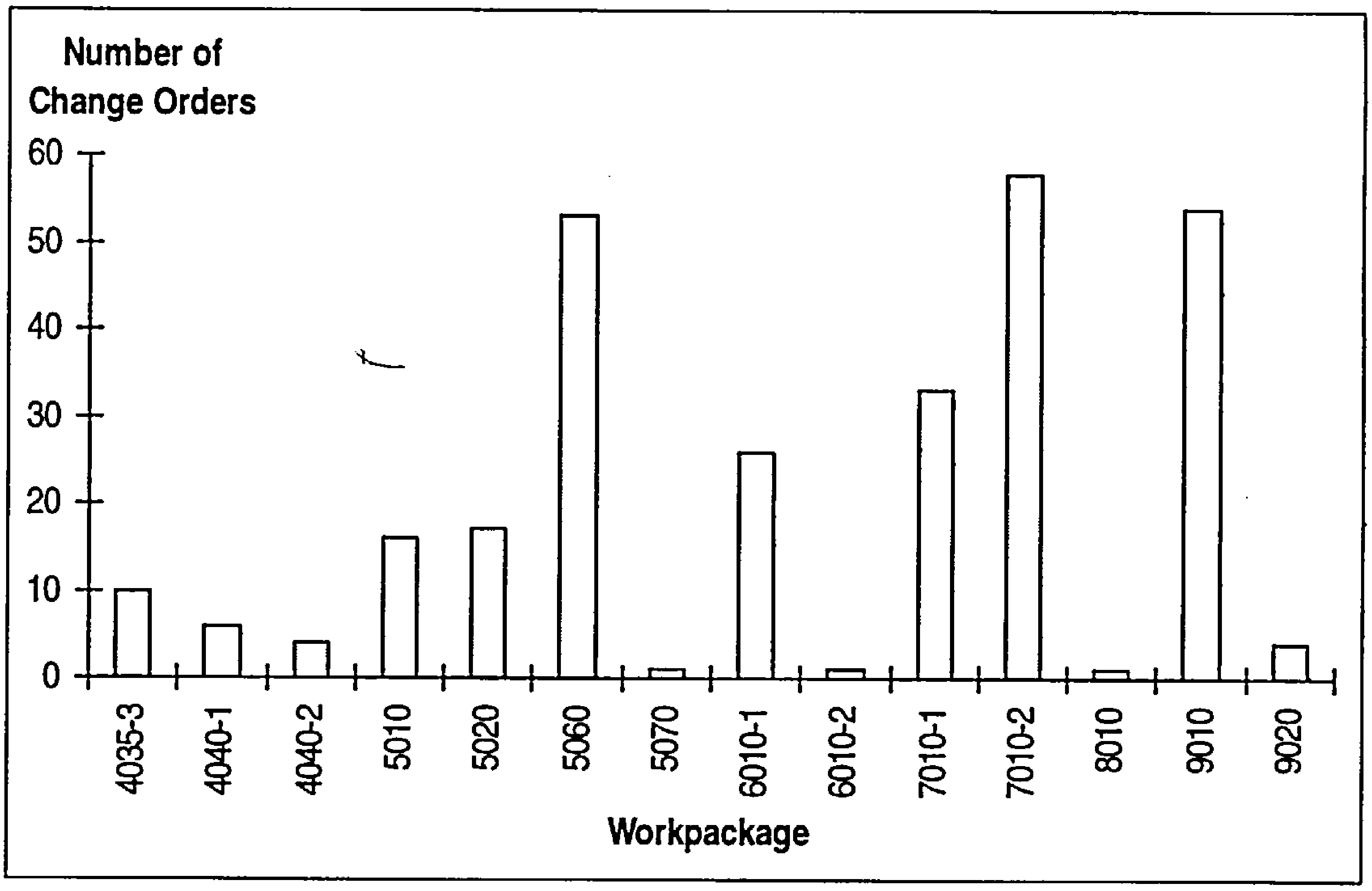


Figure 5.17b – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2)

Figures 5.18 and 5.19 show work packages 3010-1 (Substructure) and 7010-2 (Building Services – Mechanical) which can be compared with figures 5.9 and 5.13 from Cranfield University Library case study. The change orders raised against work package 3010-1 begin just before the half way point of the on site activity. The cumulative incidence of change orders is quite linear, with the last change order being raised at a fractional duration of 1.76. The cumulative cost curve shows that three design changes led to cost savings, however, a change at fractional duration 1.5 cost the project £7775. Compared with the equivalent work package in the Cranfield case study, a higher proportion of changes were made after the on site activity should have ended, however, the costs to the Cranfield project were significantly higher (approximately 2.5 – with the number of change orders approximately 1.5 times higher).

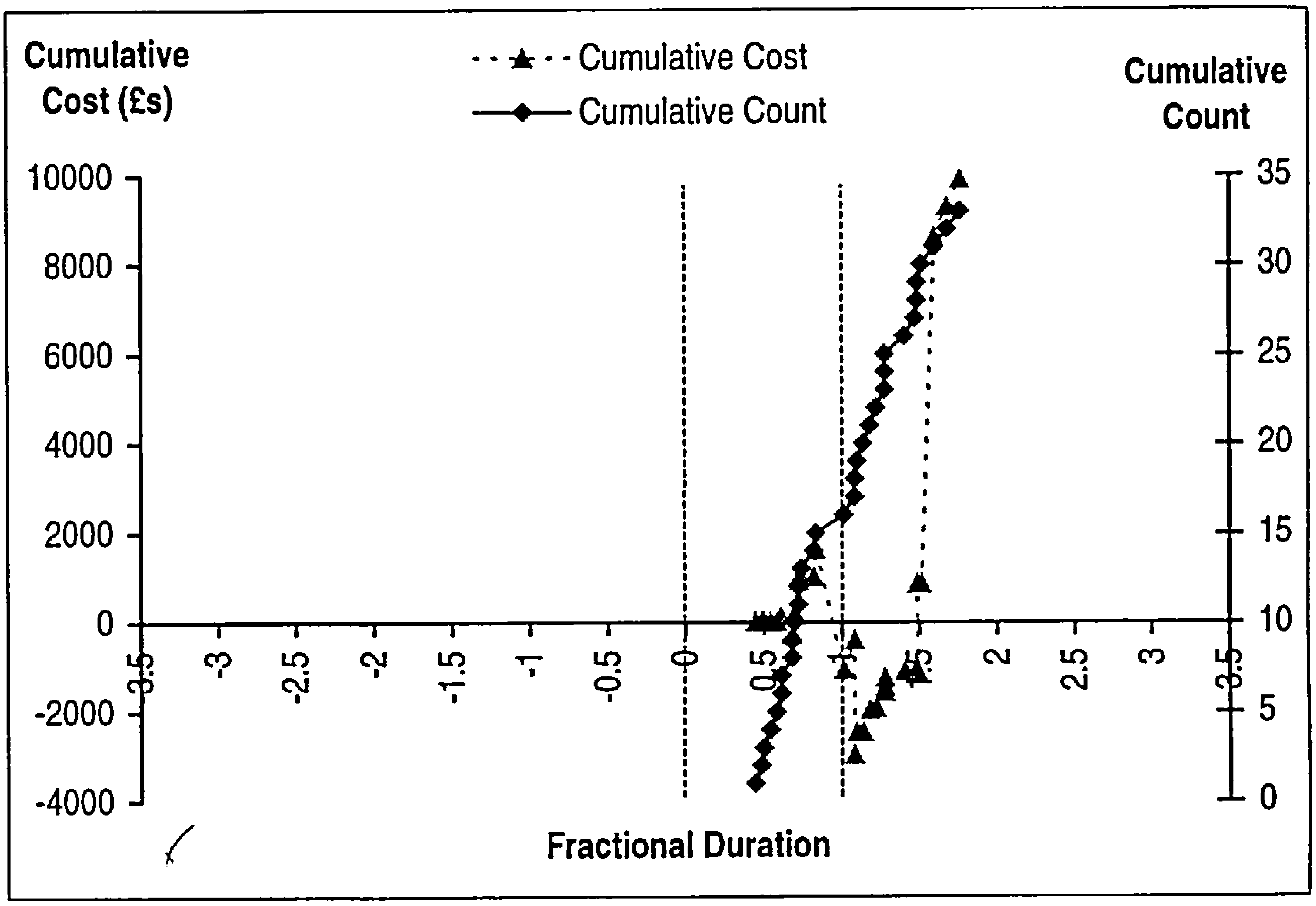


Figure 5.18 – WP 3010-1: Substructure

The most significant differences between figures 5.13 and 5.19 are the sums of money involved and the distribution of costs. The Heathrow Cargo Warehouse initiated changes on this work package far earlier than in the Cranfield case study. Only 12% of the change orders took place after work had commenced on site. The cumulative count and cumulative cost curves for work package 5060 (Fittings and Furnishings) are shown in figure 5.20. Work package 5060 had the third highest number of change orders raised against it, was the most costly in terms of fractional costs and ranked fourth for absolute cost of change orders. The cumulative count and cumulative cost curves are similar to work package 7010-2. Change orders were raised very early, starting at a fractional duration of –3.7, with 85% of the design alterations taking place prior to work commencing on site.

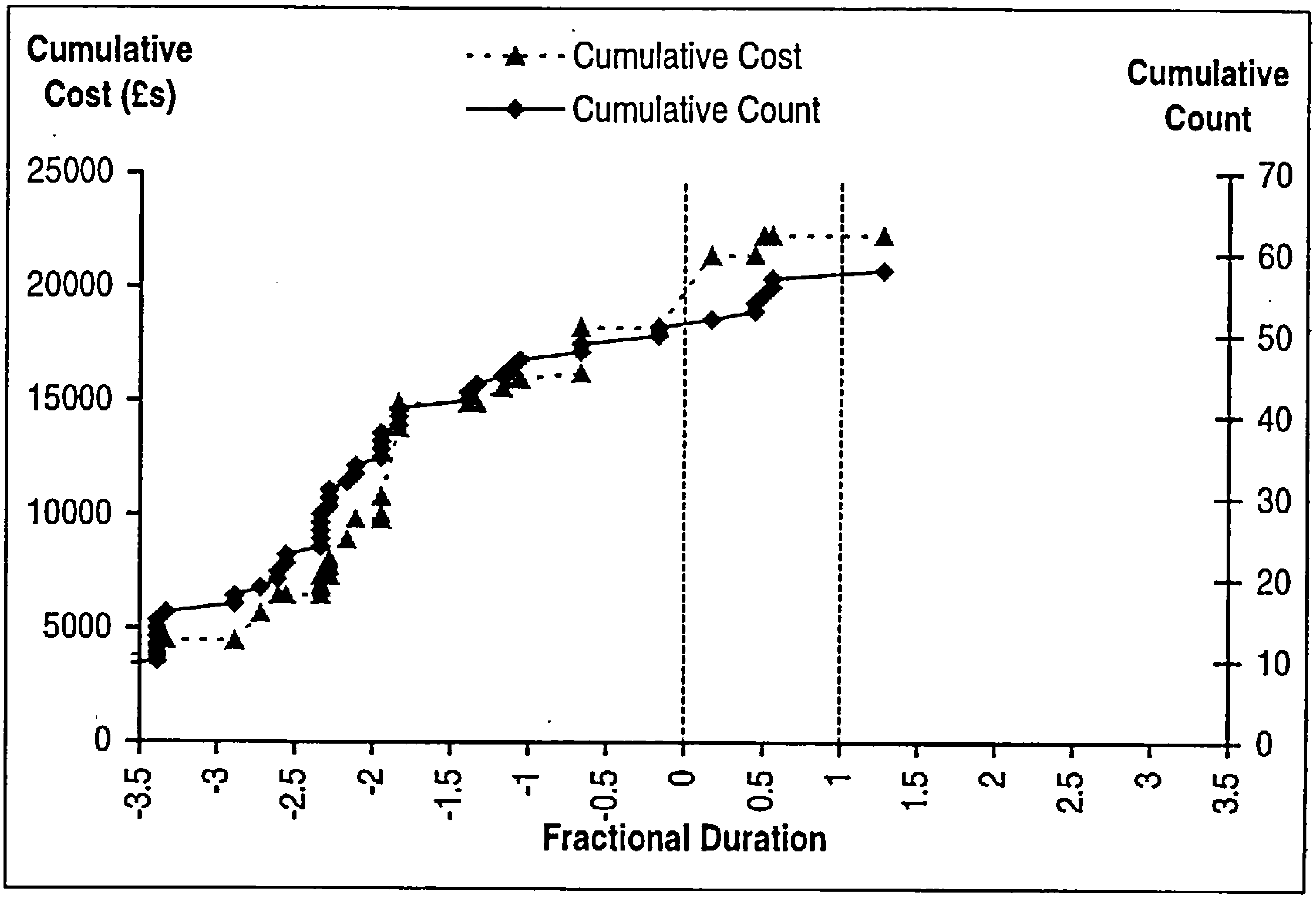


Figure 5.19 – WP 7010-2: Building Services – Mechanical

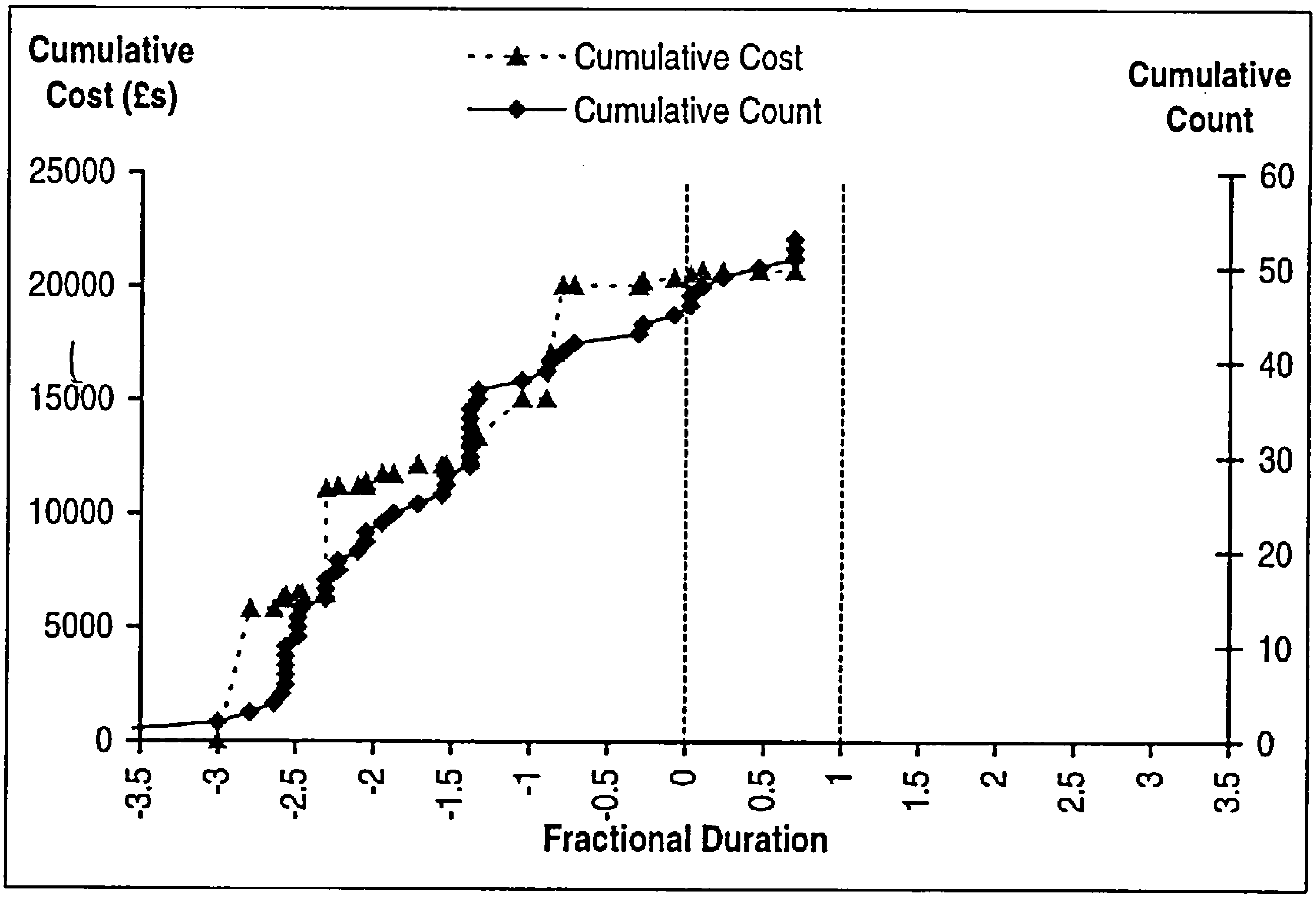


Figure 5.20 – WP 5060 Fittings and Furnishings

5.9 CHANGE ORDER REQUEST RESULTS FOR MARKS & SPENCER PRESTON

The Marks & Spencer Preston project was nominated by Taylor Woodrow Management Contracting as a case study for this investigation. The building was constructed at a cost of £5,700,732. In total 48 change orders were raised, at a cost of £323,496, which gives a *change order costs / project cost ratio* of 5.7%. None of the change orders raised had a negative cost, or cost saving to the project. Table 5.13 shows the level of interference between work packages. Only 11 change orders affected a single work package which means 75% involved multiple work packages. Where multiple work packages were involved the costs have been recorded for individual work packages, such that, in the analysis, these can be treated as individual change orders. For analysis purposes, this means that 99 change orders have been raised, the frequencies of which are shown in figure 5.21.

No. of Work Packages Affected	Work Package Names	Number of Occurrences
1	Various	11
2	1000 8520	1
2	OH+P 2120	1
2	OH+P 6260	6
2	OH+P 6510	1
2	OH+P 6760	6
2	OH+P 7410	1
2	OH+P 8410	3
2	OH+P 8520	5
3	6260 6280 6760	1
3	OH+P 5330 6760	1
3	OH+P 5830 6780	1
3	OH+P 6760 8410	2
3	OH+P 6760 8520	2
3	OH+P 6760 8910	1
3	OH+P 6780 8530	1
3	OH+P 8410 8520	1
4	OH+P 1210 3210 6760	1
4	OH+P 2120 6280 8410	1
4	OH+P 6760 7410 8410	1

Table 5.13 – Frequency of Change Orders Affecting More than One Change Order

The highest cost of an individual change order was £29,647 (Asbestos Removal: work package 4025) with the lowest at £0 (Overhead and Profit: work package OH+P). The average cost of all change orders was £6,740. Figure 5.21 shows the cost distribution of all the change orders for the case study. The raw data was categorised into classes with an interval of £500. The graph clearly shows that the most common interval for the cost of change orders was £0 to £500. This interval is represented 46 times, just over 46% of all change orders. The second most common interval is the £1,500 - £2000 which has a frequency of 7. Approximately 68% of change orders cost the project between £0 and £2000. Figure 5.21 can be compared with figures D.6 and D.6b in appendix D which show the cost distribution of all change orders based on the raw data, i.e. without applying class intervals.

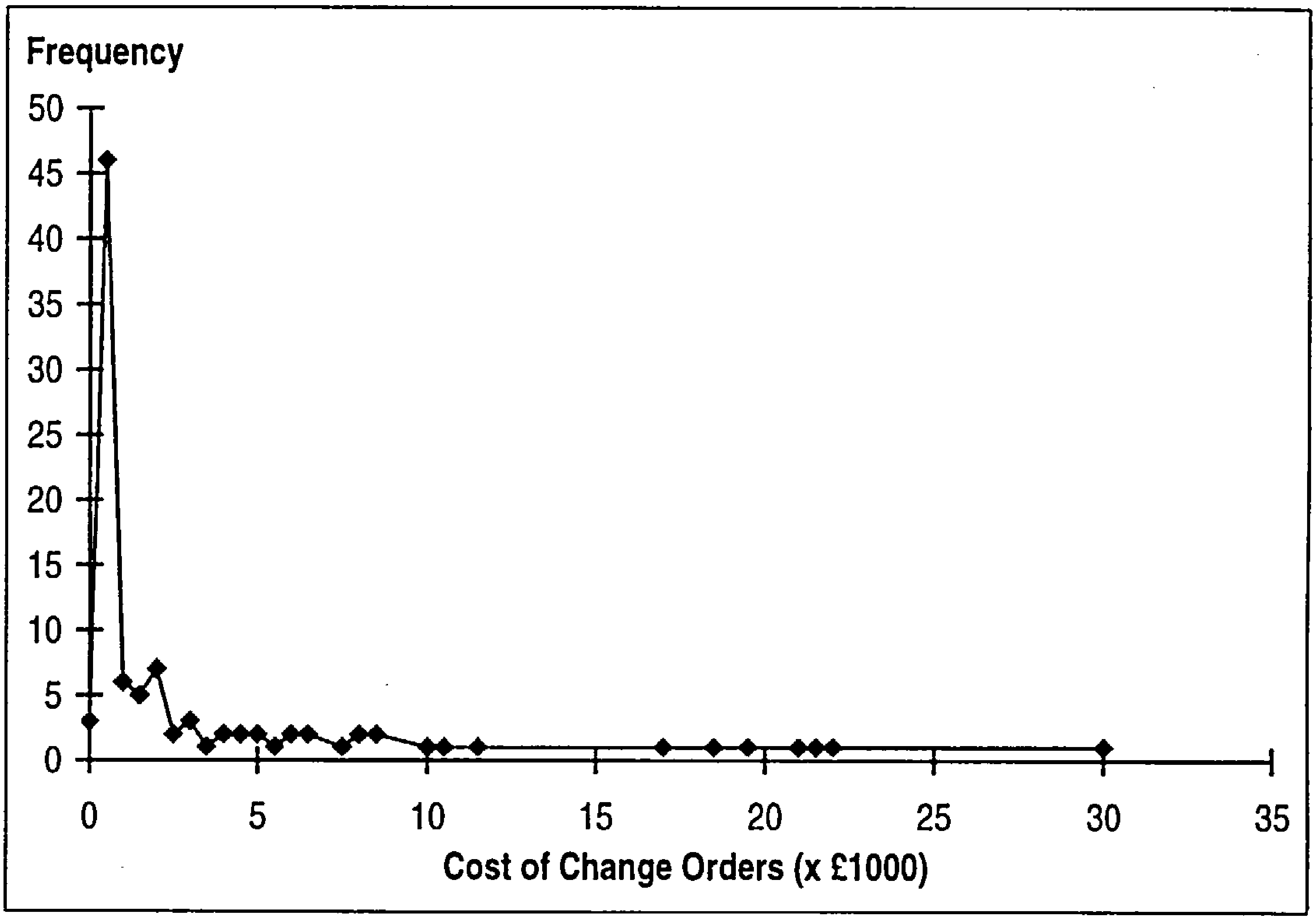


Figure 5.21 – Distribution of Change Order Costs: Cost Class Intervals of £500

Table 5.14 shows the work packages and their costs for the Marks & Spencer Preston project. It is notable for this case history that no time data was recorded (see table 5.4) therefore it is not possible to produce cumulative count and cumulative cost curves against a normalised time axis. It is for this reason that table 5.14 does not show the start and end dates for each work package. However, the table does show which of the Preston work packages have corresponding work packages in the Cranfield case study.

Figure 5.22 is the cost breakdown of change orders by reason category. The reason categories assigned were the same as those used in the case of the Cranfield library project (see table 5.7). Only categories C *(New Information on Existing Site Conditions)*, D *(Employer has changed his requirements)*, H *(Public Utility Requirement Came to Light)* and I *(Designer's Omission in Tender Documents)* were used, with D being most costly by far. The client changing his needs can be indicative of changed business circumstances, a lack of experience in refurbishment projects, a poor understanding of the total construction process or the social / political situation within the client organisation. It could also indicate deficiencies within the briefing process that need to be addressed. With the data recorded it is not possible to distinguish which is the prominent cause of change orders with this reason category.

WP Number	Work Package	Total Cost	Cranfield Work Packages WP 1	WP 2
OH+P	Overhead and Profit	£64,924		
1510	Architect's Fees	£393,662		
1000	TWMC Staff Costs	£188,701	1000	
1180	Security	£60,980		
1210	Preliminary work	£116,468		
3210	Concrete Foundation Piles	£19,636	3010	
2120	Asbestos Removal	£94,183		
5330	Cladding	£75,000	4030	4020
5830	Mirror Film	£4,000		
6260	Sales floor	£561,007	5060	
6280	Ceilings	£285,994	5010	5020
6510	Office Equipment	£39,785	5060	
6760	General builder's work	£820,000		
6780	Shopfitting (Internal cladding)	£150,000		
7410	Flooring	£215,847		
8410	Mechanical and Electrical	£1,641,298	7010	6010
8520	Refrigeration	£625,716		
8530	Fire sprinklers	£127,668		
8680	Less able lift	£13,772		
8910	Lifts	£202,091		

Table 5.14 – Work Package Costs for Marks & Spencer Preston

Tables 5.15 and 5.16 show the total change order costs for each reason category and the corresponding percentage of the costs which can be considered to be caused because of process issues. The percentage of costs related to process issues is much smaller than in the Cranfield and Heathrow projects.

Figure 5.23 shows the cost breakdown of change orders by work package with the cost split proportionally by reason category. Work package 8520 (Refrigeration) was the most costly work package in terms of absolute cost, with 6760 (General Builders Work) and 6260 (Sales Floor) second and third respectively. Normalising the change order costs with respect to the work package cost gives figure 5.24. Comparing figures 5.23 and 5.24 shows that work package 8520 is now far less important with a fractional cost of approximately 0.1 (now ranked as fifth), whereas work package 3210 (Concrete Foundation Piles) moves from a ranking of eighth in figure 5.23 to first in figure 5.24, with a fractional cost of over 0.5. Work package 3210 was affected by a single change order that was assigned to reason category C ('New Information On Existing Site Conditions'). This is shown in figure 5.25 which indicates the number of change orders raised against each work package. It also shows that a large number of low costing change orders were raised against work package OH+P (when compared with figure 5.23).

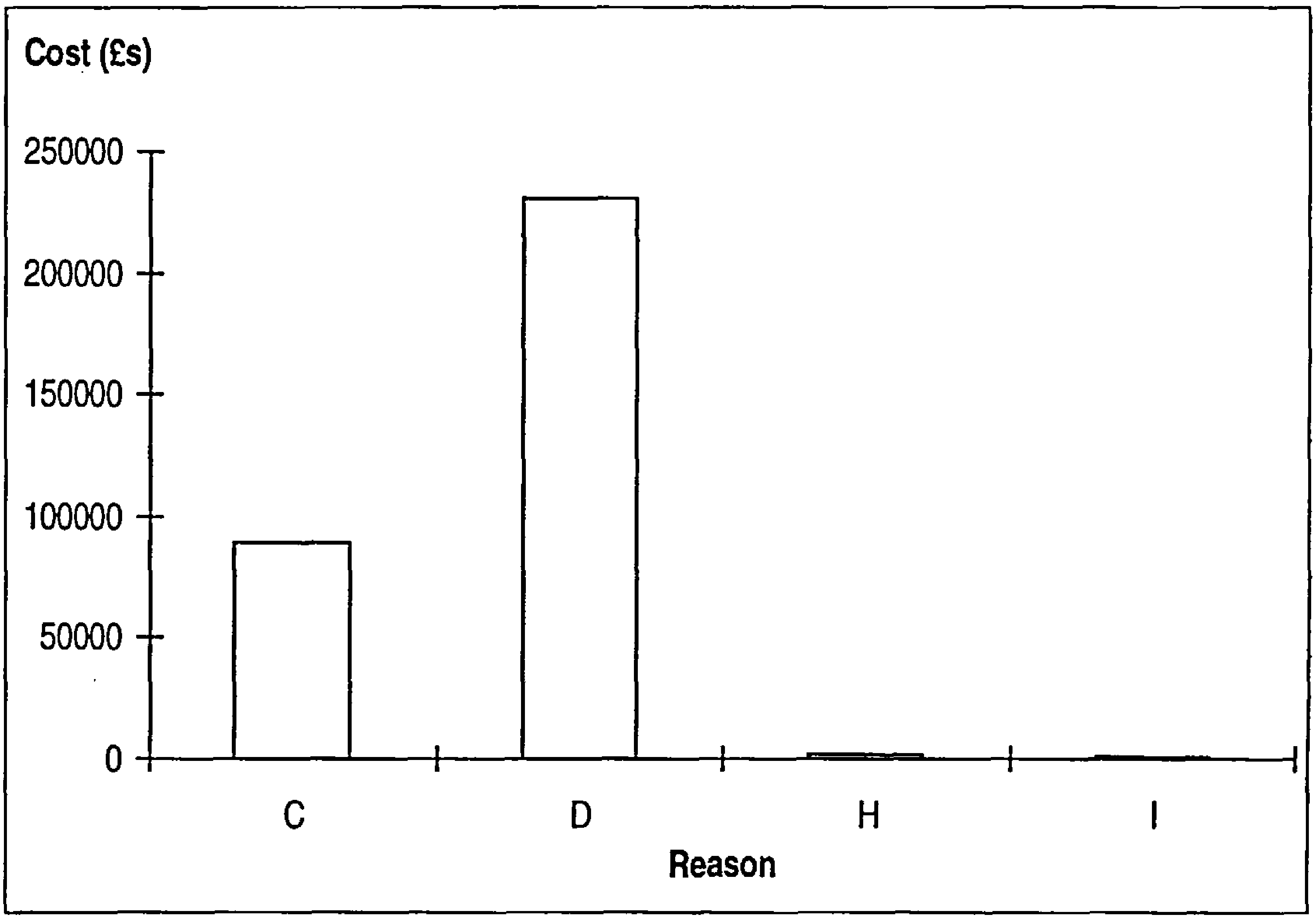


Figure 5.22 – Change Order Costs Associated With Each Reason Category

Originator's Reason Category	Cost of Change Orders (£s)
C	88865
D	230928
H	2403
I	1300
Grand Total	323496

Table 5.15 – Total Change Order Costs for Each Reason Category

Reasons	Sub Totals (£s)	Percentage of Change Order Costs Due to Process Issues
Grand Total -	323496	
Reasons I	1300	0.4 %
Reasons I + C + H	92568	28.61%

Table 5.16 – Percentage of Change Order Costs Due to Process Issues

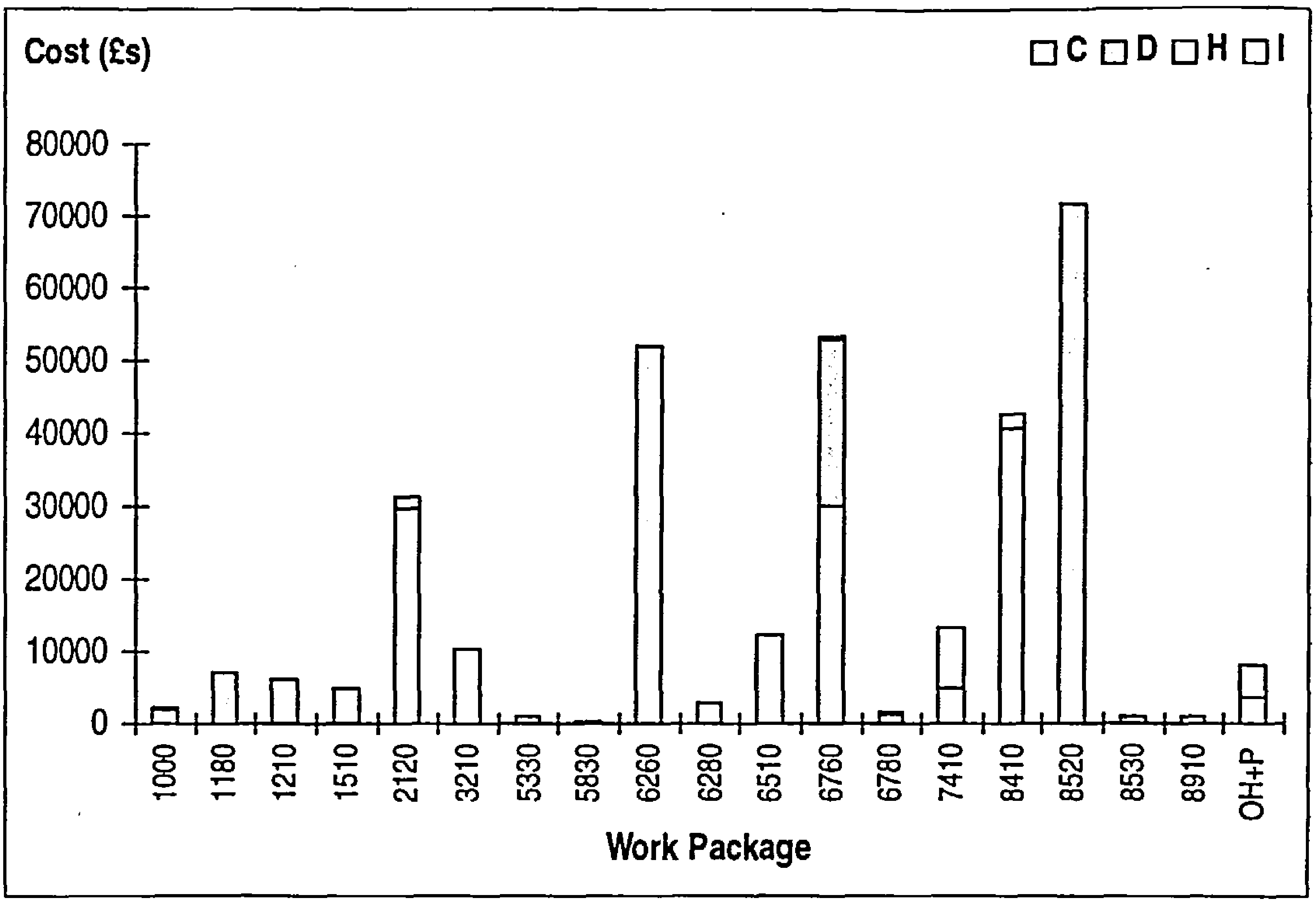


Figure 5.23 – Change Order Costs: Work Package & Reason

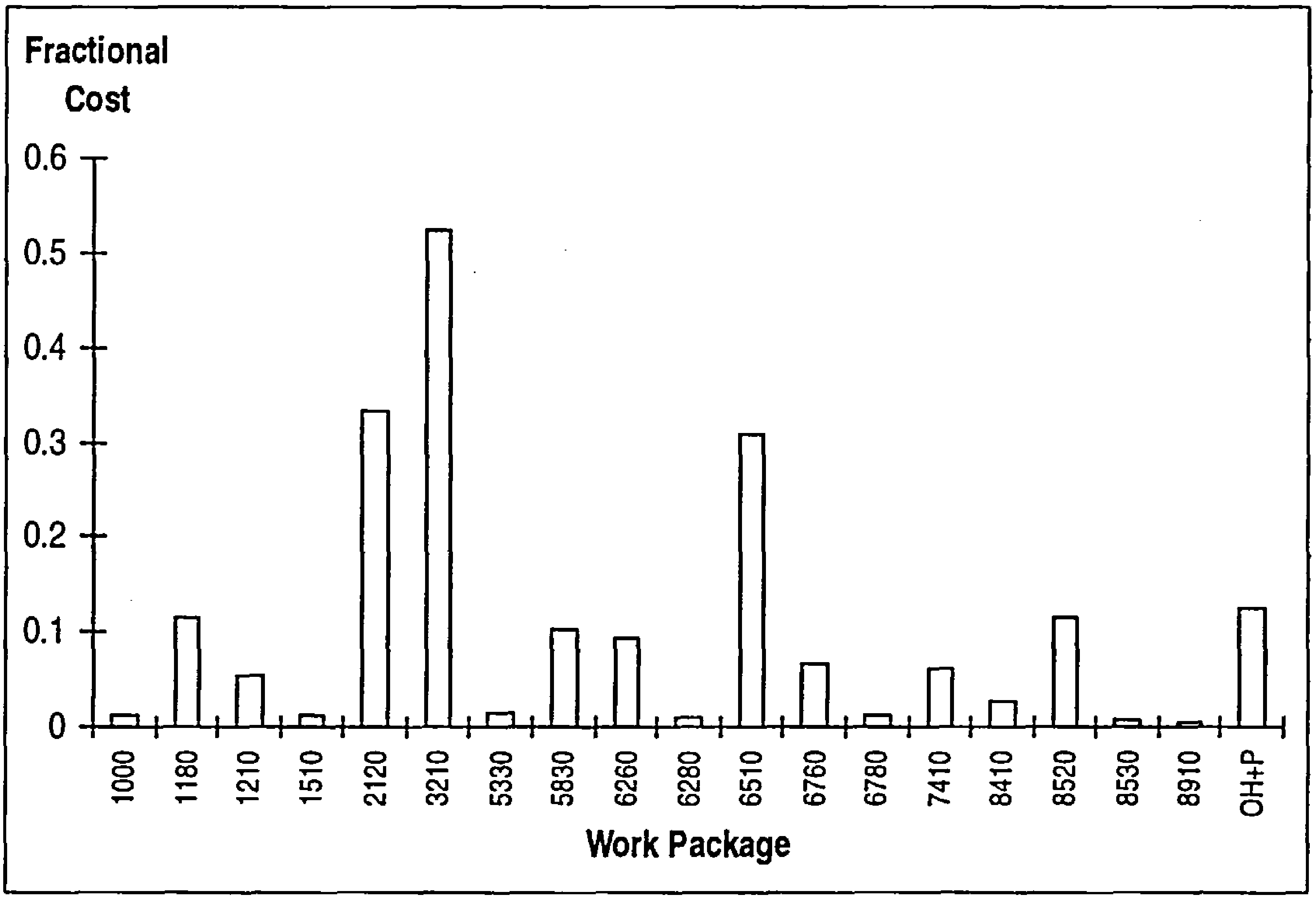


Figure 5.24 – Fractional Cost of Change Orders for Each Work Package

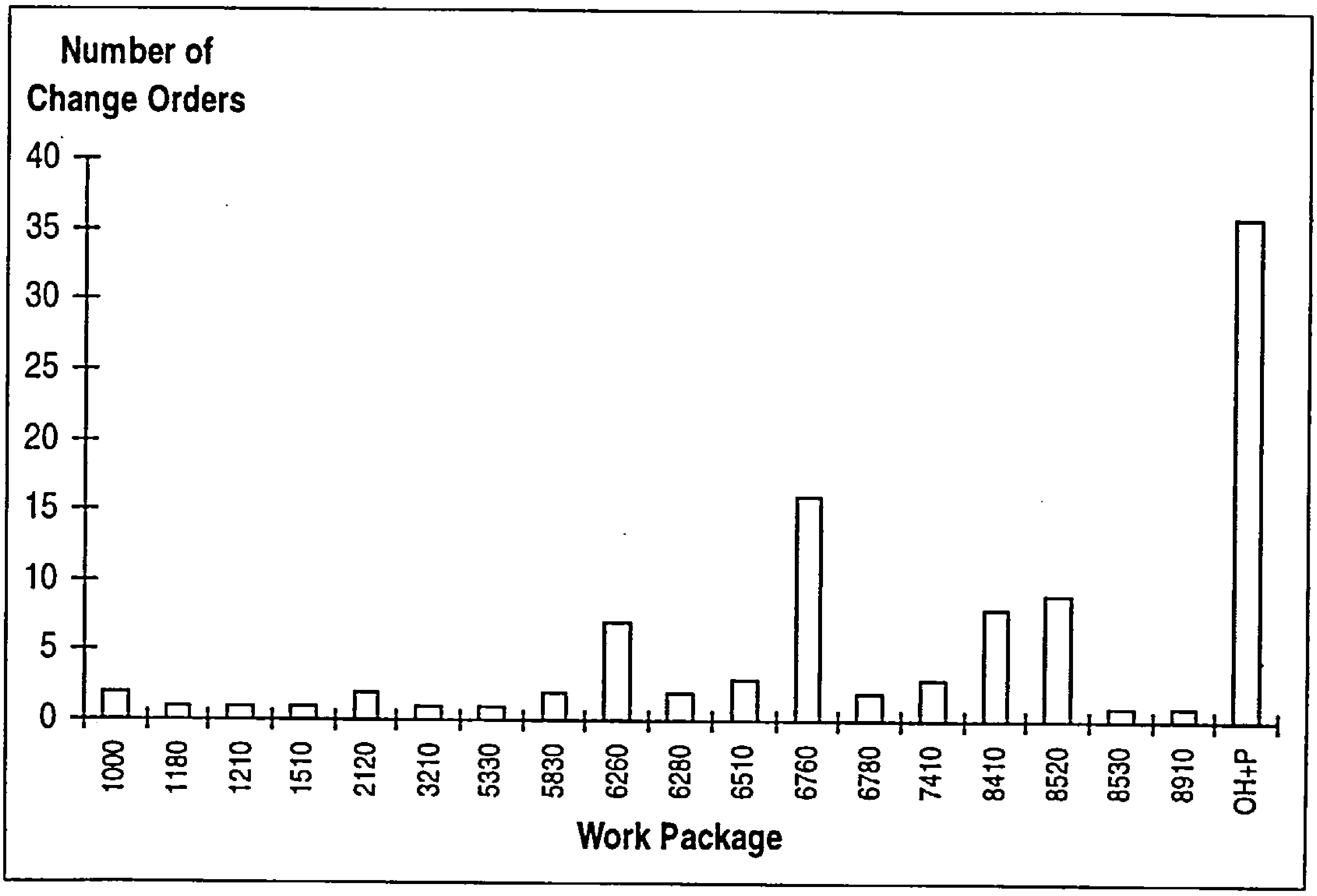


Figure 5.25 – Number of Change Orders Affecting Each Work Package

5.10 DISCUSION

In this discussion, the case histories are referred to as 'Cranfield', 'Heathrow' and 'Preston' for brevity.

The issue raised in section 5.3 was, how does the design management activity control design evolution? The RIBA model mandates that the design not be changed beyond the generation of production information and prior to the commencement of construction itself. However, the very existence of a 'change order request' process is tacit recognition of the need for changes of some kind, and the focus of process mapping was to understand why such changes occur and what the opportunity cost is of removing the need for some, or all, of these changes. More specifically, the study set out to identify:

1. The cumulative effects of change orders on a construction project?
2. Why change orders occur?
3. Which work packages are most commonly effected and why.
4. The implications for the design decision making process.

5.10.1 Change Order Costs to Project

It was found that change orders cost the case studies between 5.1% and 7.6% of the total project cost (see table 5.16). These figures amount to significant sums in each instance, £197,084 to £323,496. This confirms what was anecdotally known within the industry, that the efficiency of the total construction process can be significantly improved. The change order request system captures symptoms of *sickness* within the total process. In gauging the significance of this result, it is important to recognise that all the case histories selected or volunteered for this study were considered by their participants to be successful projects that were well managed, so these figures are certainly underestimates of the real costs incurred post contract award for a typical construction project. Furthermore, the exclusive use of cost as a measure of the consequence to the project must also underestimate the real benefit of avoiding some or all of these changes. Although there was a facility within the system to document the impact the change might have on the programme, this was never recorded. Also, it is known from the literature (Thomas and Napolitan, 1995) that change orders adversely affect productivity. Taking all these issues into account, it seems reasonable to assume that the real cost to the case histories was in fact higher than the figures outlined in table 5.16. However, the amount of additional cost is incalculable given the present data and change order request system. The impact on a typical project is likely to be higher again.

	Cranfield University Library	**Heathrow Cargo Warehouse**	**Preston Marks & Spencer**
Change Order Costs / Total Project Cost	5.1%	7.6%	5.7%

Table 5.16 – Change Order Costs as a Percentage of the Total Project Cost

5.10.2 Why Change Orders Occur: Process Inefficiencies

An important characteristic of the change order data is the reason category assigned by the originator to each request. As the originator records a category rather than a specific reason the true cause of the change cannot be gleaned from the information, however, it provides a first insight into the type of issues that necessitated the design alteration. Table 5.17 shows the most important reason categories for each case history in terms of cost to the project. It should be noted that in both the Cranfield and Heathrow case studies, L *(Other)* featured as the most prominent reason category, however, it has been excluded from table 5.17 as it is uninformative in terms of causality. It is informative, however, with regard to the effectiveness of the change order request system as it demonstrates the limitation of the reason category range. '*Other*' features as the most prominent reason category in two out of the three case studies, therefore, it is reasonable to suggest that other reason categories should be included.

Although there is some variation in the selection and order of the reason categories for each of the case studies, it is significant that there is any commonality at all. Two case histories have I *(Designer's Omission in Tender Documents), D (Employer Changed His Requirements)* and C *(New Information on Existing Site Conditions)* in their top three most costly reason categories. It is also interesting to note the importance of reason categories that relate to tender documents. If tender documents were correct first time, the Cranfield project could have avoided changes totalling £60,037, or 25% of the total cost of change orders. The figures for Heathrow are similar: £51,732, or 26% of the total cost of change orders. This identifies a particular area of weakness in the total construction process which needs to be addressed. In the Preston case study the most costly reason category by far, approximately 71% of the cost, was due to *the Employer Changing His Requirements.* In fact, this feature was recognised in discussions that took place between Taylor Woodrow Management Contracting and Marks & Spencer Ltd. following the conclusion of the project, and has already led to changes in the way joint projects are managed.

	Cranfield University Library	**Heathrow Cargo Warehouse**	**Preston Marks & Spencer**
1st Most Costly Reason Category	E Forced Upon Project by Shop Floor	I Designer's Omission in Tender Documents	D Employer Changed His Requirements
2nd Most Costly Reason Category	I Designer's Omission in Tender Documents	D Employer Changed His Requirements	C New Information on Existing Site Conditions
3rd Most Costly Reason Category	C New Information on Existing Site Conditions	J Co-ordination Defects in Tender Documents	Unimportant
Percentage of Change Order Costs Due to Process Issues	94.8% Reason Categories: E + I + J + K + C + G + H	66.1% Reason Categories: E + I + J + K + C + G + H	28.6% Reason Categories: E + I + J + K + C + G + H

Table 5.17 – Most Costly Reason Categories and the Percentage of Change Order Costs Due to Process Issues for Each Case Study

In each of the case studies the percentage of change orders that have reason categories relating to *process issues* was calculated, and can be seen in table 5.17. These figures complement the understanding of the nature of change orders outlined in section 5.3. The data showed for successful, well managed projects, carried out by industry leaders, an average of 40% (with a high of 65%) of the costs generated by change orders and 34% (with a high of 52 %) of the number of change orders were for the following reasons: *Forced on Upon Project by Shop Drawing Co-ordination, Designers' Omission in Tender Documents, Co-ordination*

Defects in Tender Documents, Management Contractor Omission from Packaging, Other and Empty. The remaining categories that the originator of a change order could select from are: *Improvement by Subcontract Design, Cost Saving Measures, New Information on Existing Site Conditions, Employer has Changed His Requirements, Programme Advantage or Assurance, Statutory Body Requirement Came to Light Since Placing the Trade Contract, Public Utility Requirement Came to Light Since Placing the Trade Contract.* If the view is taken that the briefing process (including feasibility studies, etc) should sufficiently address issues of Site Conditions and Statutory and Public Body requirements prior to the contract award then an average of 63% (with a high of 95%) of the cost of change orders, and an average of 47% (with a high of 63%) of the number of change orders analysed could have been avoided. Other design changes can be considered to be design development to add value / reduce cost, to improve the programme, or to respond to changing client's needs. From the data examined an average of only 37% of contract issue design changes can be attributed to design development per se. That is not to say that on average 63% of the cost of design changes studied were not necessary in the given circumstances, but they were avoidable. In the worst case only 5% of change order costs[4] could be attributed specifically to design development (Cranfield case study). It is this 63% of change order costs that can be directly addressed by improving those activities which the design team has control over. Which leads to the question, 'What was deficient about the design decision making process that necessitated a change order?'

Although engineering changes are the direct equivalent of change orders, both can be thought of as analogous to rework in the production stage as both represent waste in the design process. Rework in the production stage is not just attributable to manufacturing issues but, from a process management perspective, represents waste / imperfections in the *total* delivery process. Rework is a term usually associated with the production process as this is often where the imperfections in the total process are realised. In some cases rework maybe attributed to a specific manufacturing problem such as an inappropriate tool, but in others it is merely symptomatic of the fact that the product has been designed in such away that it is not well matched to its delivery processes or there is a failing in the way design information is transmitted and / or used to produce the article. This includes all activities from concept design through to manufacturing the product. Change orders are the *rework of the construction design process* and, similarly to manufacturing, are largely encountered / realised in the building phase. Mohamed and Tucker (1996) posit rework as an issue mainly associated with client dissatisfaction at the end of a process and cite variations and errors to be the main two causes of rework. They go further by stating that variations are caused by the inadequate capturing and meeting clients' requirements whilst errors occur because of improper application of quality measures. It is often posited that change orders do not constitute waste but are rather a natural part of design evolution which serve to improve the building by either adding value / cutting costs, responding to changing client's needs or to make improvements to the

---

[4] That is 5% of the net cost, i.e. the data set included change orders with negative costs or cost savings to the project which were attributed to reason categories associated with design development. For this case study, total change order cost savings/total change order costs ≈ 11%

programme. This is certainly true for a proportion of the change orders investigated, however, it should now be recognised that this view is only a part of the story. The reasons why change orders occur needs to be investigated more thoroughly. Change orders are symptomatic of inadequacies in the upstream processes and improvement of these processes offers a significant opportunity for improving the overall performance of the construction industry.

5.10.3 The Work Package Dimension

There were two perspectives of the importance of work packages and the incidence of change orders: cost of change orders as a fraction of the work package cost and the absolute cost of change orders affecting a particular work package. Table 5.18 shows the four most important work packages for each case study in terms of fractional cost. There is little commonality between the projects. Landscape / Drainage and Mechanical Services appear in both the Cranfield and Heathrow top four, although in different positions. Preston does not share a single work package with either of the other case studies.

	Cranfield University Library	**Heathrow Cargo Warehouse**	**Preston Marks & Spencer**
1st Most Costly Work Package	Architectural Metalwork	External Works (Landscape / Drainage)	Concrete Foundation Piles
2nd Most Costly Work Package	Blockwork / Partitions	Building Services: Mechanical (2)	Asbestos Removal
3rd Most Costly Work Package	Mechanical Services	Office Roof (2)	Office Equipment
4th Most Costly Work Package	Landscape / Drainage	Doors and Ironmongery	Overhead and Profit

Table 5.18 – The Most Costly Work Packages in Terms of Fractional Cost for Each Work Package

The situation is somewhat different when the absolute cost of change orders are affecting a specific work package are considered (see table 5.19). Mechanical and Electrical Services are especially prominent, appearing in each project's top four most important work packages with Fittings / Furnishings equal third place for Heathrow and Preston. This should be a cause for concern for project teams, services engineers in particular. The differences are likely to be due to a combination of factors. Firstly, there is the issue of separating tasks into work packages and the criteria used to achieve an appropriate arrangement for each project. This can lead to change orders arising because of interface issues where different contractors install adjacent / interacting work packages. Also, work packages in the analysis which are described as equivalent will have some variation at the task level which could cause some change orders relating to the same task to be attributed to different work packages. It is also possible that each project will have a unique change order characteristic, i.e. there will be variation in the results. However, as the research methodology is centred on case studies to gain a broad insight into the issues affecting change orders rather than a statistical sample, it is not really possible to make the generalisations that are desirable.

	Cranfield University Library	Heathrow Cargo Warehouse	Preston Marks & Spencer
1st Most Costly Work Package	Mechanical Services	Landscape / Drainage	Refrigeration
2nd Most Costly Work Package	Blockwork / Partitions	Building Services: Mechanical (2)	General Builders Work
3rd Most Costly Work Package	Electrical Services	Fittings / Furnishings	Sales Floor (Furnishings / Fit-out)
4th Most Costly Work Package	Substructure and Concrete Frame	Building Services: Mechanical (1)	Mechanical and Electrical Services

Table 5.19 – The Most Costly Work Packages in Terms of Absolute Costs of Change Orders Affecting Each Work Package

5.10.4 Cumulative Count and Cumulative Cost of Change Orders

The cumulative count and cumulative cost graphs for each work package offer a novel way of assessing the cumulative affects of change orders on a project. The system currently used in industry considers each change order on an individual basis which does not provide the visibility required to manage cost build up effectively. It provides no insight into problem work packages as the request documentation is often filed and forgotten. These graphs display the cumulative affects of change orders raised against a particular work package and facilitates the ability to compare dissimilar work packages within a project and similar work packages across projects. Although comparisons were made with the information available, no general principles could be identified because of the limited number of data sets. Again, this is a limitation encountered through the use of case studies rather than a statistical sample. In these case studies it was found that a significant number of the work packages had changes made to them before, during and after on site activity. It is desirable that any changes made are implemented prior to work commencing on site as they tend to cause less disruption. Indeed, the earlier a change is made, the better.

If a large amount of data were available it is considered likely that generalisations would be identified. For instance, individual work packages may have a characteristic curve which may be due to the nature of the work package, such as complexity or the strategy adopted by the design team. Such knowledge could be used to improve the total product delivery capability and foster a culture of process improvement within the construction sector. If systematised, this method could be used as a real time project management tool. The information recorded could flag up problem work packages to the design team allowing them to implement remedial action to limit the number and cost of design changes. However, the greatest benefit to the industry will be to use change order data to help reduce the number of errors occurring in the up stream processes by producing a large number of data sets in a form which can easily be analysed.

5.10.5 Other Issues

An incidental but important finding of the work is that the data examined was kept in a relatively inaccessible form which made analysis difficult. In each of the case studies the data was recorded in a paper based system. However, since that time some of the partners have adopted electronic systems which make data processing easier. Another issue of concern was the quality and completeness of the records. The case studies involved organisations that can be considered to be of good reputation within the industry and were thought of by these companies to be well managed projects. However, the completeness of the records was quite poor. As a result of this, only three out of the four case studies offered could be processed. It was also of concern that nothing was really done with the data. The system does offer some degree of controlling contract issue design changes by virtue of having a procedure for requesting and approving modifications, but it would seem that the lack of analysis of the available data is indicative of a lack of process improvement culture in the industry. This leads to the rationale behind the system. The procedure, as acknowledged, is in place to control contract issue changes but it is with a view to managing the cost from a contractual perspective. In other words, because a particular modification has been made for a particular reason, there needs to be some control mechanism for reimbursing the contractor or subcontractor. This is a perfectly legitimate system which facilitates additional monetary transactions from the client to appropriate party, but it reinforces the view that few, if any, systems are in place to gather data with the specific intention of monitoring the health of the product or processes by which it is delivered. To this end, the change order request system could be modified to allow it to continue to control the change process as it currently does, but to collect data with a view to identifying more accurately the *root causes* of change. This data could be gathered, analysed and acted upon. This could be achieved by implementing a two stage system. The first stage would be similar to the existing system, with an increased number of, and more appropriate, reason categories. Greater emphasis could also be placed on indirect costs such as the impact to the programme. The second stage could be used to identify the root cause of the change order, recording the key factors involved in the initial design decision. Analysis of this data could be a means of improving upstream processes.

5.11 CONCLUSIONS

The main finding of this investigation is that change orders cost between 5.1% and 7.6% of the total project cost for the well managed and successful projects studied. These figures are likely to be an underestimate for typical projects by virtue of the case histories alleged success. Also, the figures are based purely on direct costs to the project and take no account of the impact on productivity, disruption to the programme, etc. Nevertheless, they represent significant sums of money which the design team should be concerned about.

A means of showing the cumulative affects of change orders on a construction project has been demonstrated. The technique considers the incidence of change orders and cost build up on a work package basis over a normalised time axis. This approach facilitates comparisons of dissimilar work packages within a project and similar work packages across projects. However, it was not possible to make generalisations from the available data. A significantly larger data set would be required to identify trends on a work package basis. A larger data set could be more easily obtained if data were recorded electronically and all sections of information completed. Showing the change order costs as a fraction of the work package costs also provides an insight into the total cost of change orders raised against a particular work package.

Change orders occur for numerous reasons. Frequently cited reason categories include: *Designer's Omission in Tender Documents, Co-ordination defects in Tender Documents, Forced Upon Project From Shop Drawing Co-ordination, Employer Has Changed His Requirements and New Information On Existing Site Conditions.* The system in place does not record the specific cause of a change order but rather a broad reason category which provides a reasonable insight into the nature of the cause. In particular, this case study sought to separate the reason categories into two classifications: process issues and non-process issues. That is, issues which the design team have a large degree of control over (or potential control) through their work practice and project strategy, and those issues which the design team has little or no control over. It was found that an average of 63% (with a high of 95%) of the cost of change orders related to process issues, on the basis of the projects studied. This suggests that the majority of change orders actually constitute waste in the pre-site activities, i.e. the *total* design process. This supports the concept that change orders are the rework of construction design. Due to the limitations of the change order request data, further study of the activities which make up the *total* design process is necessary to identify the root causes of change orders and, hence, inefficiency in the system. It was also found that a significant number of change orders (and change order costs) were attributed to deficiencies within the tender documents. More time and energy spent on producing accurate tender documents prior to the contract award could save significant sums of money.

There was little commonality shown in the importance of similar work packages, in terms of cost of change orders, across the projects. However, Building Services: Electrical and Mechanical was identified as a problem work package in all three case studies.

It was found that the change order request process itself was aimed primarily at handling the contractual implications of late design changes rather than implemented as a process improvement tool. It was also found that the reason categories used are too limited. In both the Cranfield and Heathrow case studies the reason category *Other* was the most commonly cited indicating that some other reason categories should be included, although it is not possible to say what they should be. The reason categories themselves are also subject to the objectivity of the system, i.e. they reflect the contractual issues that might arise. During projects the data was only considered on an individual basis with no analysis performed. This confirms that the system is not used for process improvement purposes. It is a conclusion of this study that the change order request system could be modified to incorporate a process improvement philosophy, whilst still containing sufficient elements of the system to control the modification of the contract issue design. A new system could place greater emphasis on issues other than direct cost when calculating the impact that a contract issue design change will have on the project.

The most significant finding of this research, is that change orders are symptomatic of problems occurring within the design process. The data studied does not indicate what the problems are but rather points an ‘accusatory finger’ towards the early decision making process. The study has identified where the problem lies and provided some idea of the potential saving to be made. However, to realise these savings an investigation into the design decision making process is required. This reminds us of the question that was raised in the discussion in section 5.10.3 which asked, ‘what was deficient about the design decision making process that necessitated a change order?’ It is proposed, therefore, that the next stage of the research should focus on the decision making process to identify the key issues involved. The research should have the aim of identifying how the design process can be made more efficient and efficacious.

5.12 SUMMARY

This chapter has detailed the analysis of the consequences of poor design decision making. The investigation was an exploratory study into the affects of contract issue design changes on construction projects. Data was used from a number of case histories to identify the key issues involved. Graphical techniques used include bar graphs showing:

- *cost* vs. *reason category*, with the cost split proportionally by *originator*
- *cost* vs. *work package*, with the cost split proportionally by *originator*
- *cost* vs. *work package*, with the cost split proportionally by *reason category*
- *fraction of work package cost* vs. *work package*
- *change order request count* vs. *work package*

and a series of line graphs showing:

- *cumulative cost* & *cumulative count* vs. *fractional duration* (line graph)

The findings of the study have led the author to conclude that the need for a significant proportion of change orders is due to issues in the control of the design team in the early design stages. Therefore, it has been proposed that further investigations into the design decision making process should be conducted with a view to establishing a means of improving the efficiency and efficacy of decision making, through better control of the process.

The development of an Electronic Data Gathering Tool (EDGT) to map design decision making is detailed in chapter 6.

CHAPTER 6 ELECTRONIC DATA GATHERING TOOL

> *"With all due respect and patience to structural engineering elitists, computer scientists, management gurus, clients of structural engineering services, and computer oriented politicians who are fascinated and infatuated by the so called electronic information revolution as a panacea of structural engineering information processing, this is pure fairyland gobbledegook! ... Quality structural engineering can only be performed by knowledgeable, intelligent, innovative and creative structural engineers with extensive practical design experience, rather than by computer technicians pressing keyboard and mouse buttons while viewing computer boob tubes!"* **Professor Leroy Z Emkin, Georgia Institute of Technology (Misuse of Computers by Structural Engineers: A Clear and Present Danger)**

CHAPTER 6 ELECTRONIC DATA GATHERING TOOL 119
6.1 INTRODUCTION 120
6.2 INITIAL INVESTIGATION 121
6.3 OBJECTIVES 125
6.4 TOOL DESIGN 126
6.5 USING THE ELECTRONIC DATA GATHERING TOOL 134
6.6 DISCUSSION 137

6.1 INTRODUCTION

The analysis of the change order request data revealed that a large percentage of the cost of change orders were due to inefficiencies / deficiencies within the design decision making process (see chapter 5). It was found that the cost of change orders was between 5.1% and 7.6% of the total project cost, although these figures are likely to be an under estimate of the real cost to projects as direct cost to the project is a limited measure of consequence. That is, there is an opportunity to save between 5.1% and 7.6% of the total project cost by alleviating the need for contract issue design changes. In case studies analysed, it was shown that 63% of the cost of change orders related to process issues, or issues that the design team have a large degree of control or influence over. Although reason categories were assigned to each of the change orders the resolution of the categories lacked the specificity to identify the root causes of the need for design changes. Whilst the categorisation is reasonably adequate from a project management perspective it is of only limited use from a process improvement standpoint. Therefore, to gain the desired insights into the design process, and to improve efficiency, a detailed investigation of the design decision making was necessary.

At this stage two options are open:

1. Try to identify root causes of change orders by interviewing design teams and working out ways to eliminate change orders, thus saving 5 - 8% of the total project cost.

2. Take the notion of change orders as a general malaise of the design process and then do further investigation to try to improve control of the design process and, hence, make savings.

It was decided to select option two, primarily because it was considered to present a bigger opportunity to gain insights into construction design, and thus make recommendations for improvement. It is also accepted in the literature that the ability to influence cost in a design project diminishes with time (for example Chen & McGeorge, 1993/4, Yamigawa, 1994). Other, more practical, considerations also came into play, such as the design teams from each case study considered in chapter 5 have long since dispersed, and the individuals concerned are unlikely to remember the issues involved with particular change orders in sufficient detail to provide the desired insights. It would therefore be necessary to collect new data sets of change orders and carry out a similar analysis to that previously performed but also try to identify the route causes of specific change orders by interviewing design team members as design changes arise. From a research management perspective, it was deemed undesirable to repeat the previous study, and it was thought that a larger process mapping exercise may provide far reaching implications for construction design. Also, previous work by Austin et al (1996) has focused on optimisation of design tasks / design task planning at the detailed design level. There appeared to a gap in the knowledge of understanding how design decision making works at the system / sub-system level.

Having established that it is desirable to process map the construction design decision making process, three key questions arise:

1. What aspects of the design decision making process should be mapped?
2. What level of detail should be investigated?
3. How is data to be gathered and analysed?

To try to address these issues a preliminary investigation was conducted into the design process by interviewing a number of architects from industrial partner companies.

6.2 INITIAL INVESTIGATION

At this stage of the research the broad subject matter for further investigation had been identified, namely the design decision making process. However, it was not clear in the first instance which was the best way to approach the task. Detailed studies of design have been made using protocol analysis (Chan, 1990; Baya & Leifer, 1994 & Lloyd and Scott, 1994). However, this mainly deals with the psychological perspective of design, i.e. relating to individual designers. Given the author's understanding of lean thinking, protocol analysis was deemed unsuitable. An approach that considered design interaction at the organisational level was likely to be more appropriate.

6.2.1 Objective of the Interviews

The objective of the interviews was to identify the issues that would be likely to provide insights into how to improve the efficiency and control of the design decision making process in construction projects and, hence, make construction design lean.

6.2.2 Interview Format

Ten architects from the Stanley Bragg Partnership and Sir Norman Foster and Partners were interviewed. The interviewees were largely senior architects with the five from the Stanley Bragg Partnership also being company directors. The interviews lasted approximately 75 minutes. Each architect was asked the same questions with the exception of questions 1b, 8 and 9. Question 1b was only addressed to architects at Stanley Bragg Partnership and questions 8 and 9 only to architects from Sir Norman Foster and Partners. The Stanley Bragg Partnership interviews were conducted first and it was deemed appropriate to modify the list of questions on the basis of that experience, i.e. question 1b was removed and 8 and 9 added.

The following is a list of the questions asked:

1. What affects the development of a concept design the most, the individual architect who has been assigned the task of producing the concept or the framework in which he / she works?

1b. Can you give me a brief outline of the design process as you see it from the inception of the project until the construction phase takes place? [Stanley Bragg only]

2. Can you explain the briefing process?

3. What information is gathered to support the brief and assess its feasibility?

4. Do you define important parameters / factors which need to be considered in design solutions?

5. Having now developed a comprehensive understanding of the brief (and hence the client's needs) and some of the important constraints involved, how do you go about translating that into a concept design?

6. How do you work in the concept stage?

7. Do you consider such factors as cost implications, assembly and construction techniques in the conceptual design stage?

8. Is it typical to follow the RIBA guidelines for every project? [Foster and Partners only]

9. What problems typically occur on site that are directly related to design? [Foster and Partners only]

The interviews were recorded, with the five most informative (3 Stanley Bragg and 2 Sir Norman Foster and Partners) transcribed and analysed. The key themes contained within the responses for each question have been presented in the form of fishbone diagrams in appendix E. The interviews were unrestrained with regard to the responses that were permitted.

The questions are very broad and touch upon briefing and design, and their interrelation with buildability. The line of questioning with regard to design is focused upon concept design phase as, according to McGeorge & Palmer (1997), there is more scope for affecting design in the earlier stages of the process, and it was assumed that systems level decisions are largely addressed in the concept stage. Buildability is of interest as, although the need for change orders has its origins within the design decision making process, it is often realised in the production stage.

6.2.3 Issues Arising From Interviews

The interviews provided first insights into the characteristics of the construction design process. There was a very broad range of answers given to the questions which was both anticipated and welcome. The architects used numerous examples of their work as a basis for their responses. It was found that they discussed the same issues in some cases but not in others. Sometimes they contradicted each other directly other times suggesting that different factors were of greater or lesser importance. The design process that they described varied considerably and lacked a prescriptive format or approach. Indeed, the way in which architects work in the concept design stage was said to be both *project and client specific* (see appendix E page 13). The idea of a controlled process appeared to be highly unpopular with some of the architects who spoke of the *fuzziness* and *mystery* of design. With regard to formal methods used, one architect highlighted that the RIBA stages are *only an approximation to the real process.* The stages are intended to bring order to the complexities found in construction projects and indicate to clients what type of activities the architect should be performing at a given point in time. It also facilitates a means of paying the architects for their professional services. Therefore, the stages do not really control the design process as some product development processes in manufacturing do, or the process protocol developed by Salford University (Kagioglou et al, 1998), but provides a means of conceptual representation. This is an interesting point as *management structures* were cited as being influential in the development of concept designs (see appendix E page 7). A key finding is indicated in the responses to question 7. It was revealed that there is a *generic content to most buildings* and that it is *rare for a building to be completely new* (see appendix E page 14). The question arises to what extent is there a generic content between buildings and, therefore, the design decision making process which produces them? Also, is it possible to identify this generic content and use this knowledge to help provide a greater degree of control to the design decision making process?

The interviewees also indicated that a number of options are considered during the decision making process and that multiple *drivers* or reasons form the basis on which selections are made, although it was not clear to what extent designers are consciously aware of them. It is also apparent that the designers have to take into account design *considerations*, or constraints, when choosing between design options. Some of these constraints are outlined in the brief, some imposed by the planning authority and others emerge as the project proceeds. It was found that a number of people are regularly involved in construction design and that the interaction of these people is an important factor for the development of concept designs. Projects often have a design team comprising an architect, structural engineer, services engineer and quantity surveyor. A number of specialist consultants will also contribute to the decision making process at various stages, as will suppliers. Although these key roles will usually be employed within a project the contractual allegiances may differ depending upon the client's preferred procurement route. The level of input from any of these individuals varies on a project basis, as does the timing of their appointment.

A mixture of hand sketches and Computer Aided Design (CAD) are used frequently within the concept design stage, with greater emphasis placed on CAD as the design is firmed up. The interviewees did not reveal how much IT is used in the design process nor the activities that IT facilitates. A significant amount of information is also gathered or referred to when generating the brief and making decisions. Problems can occur when information is missing or incorrect. It was indicated that IT plays a significant role in some instances but not in others. It was not clear what these instances were. The briefing process is an important aspect of construction design as the designer elicits knowledge from the client regarding the buildings functional requirements. Equally as important to technical issues are the commercial ramifications of the project in terms of the client's desired return on investment and the level of acceptable risk. The designer also attempts to understand the aspirations of the client that are non-technical, such as political, social and personal desires, and also identify priorities. This prioritisation is usually implicit to the process rather than employing formal methods such as Quality Function Deployment (QFD) (see section 2.5.3.1). The design process is then an attempt to synthesis all the factors that are revealed through briefing into a balanced product.

6.2.4 Conclusions

A key issue identified from the interviews was, to what extent is there a common design decision making process across projects? It was stated that *'it is rare for a building to be completely new'* and that there is *'a generic content to most buildings'*. The author has taken the view that if there is a generic content to most buildings in the physical sense then it is likely that there is a generic content to the design process that produced them. Therefore, any attempt to process map the design decision making process in construction should try to assess the amount of generic decision making across projects. This has a direct link to the lean thinking approach. In section 2.2.4 of the literature survey, the concept of 'standardised work' is introduced to the product development process. Identifying a generic content to the design decision making process in construction projects could lead to a more standardised design method.

An advantage of mapping the design decision process is that it goes some way to mapping the value stream (see section 2.2.2.2) – another requirement of lean thinking. This is usually achieved by mapping in the task domain all the tasks which are required to develop the product. The tasks are then divided into three groups: those which add value directly, those which do not add value but are unavoidable, and those which do not add value and are avoidable. The mapping of the design decision making process is not strictly speaking the value stream as it operates in the level of abstraction of 'decisions made' rather than 'tasks performed'. As, by definition, the decision making process is that of value generation, mapping the decision making process will only deal with activities which directly add value to the product. Nevertheless, this is a valuable exercise as it precisely identifies a particular group of value adding activities, namely system and sub-system level design decisions.

Other issues identified through the interviews, which could be incorporated into the process map, include:

- The use of tools to support the decision making process
- The information sources consulted

- The influence of different players within the design team
- The design 'issues', or constraints, impinging upon a decision
- The number of options considered and the reason drivers used to choose between them

Briefing was also identified as a crucial factor in the total construction process[5].

6.3 OBJECTIVES

In the light of the findings from the interviews, and influence of the literature survey, the following objectives were decided upon for the development of a data gathering tool:

1. To develop a tool that can gather data for mapping the design decision making process in construction projects. From the data gathered, it should be possible to identify if there is a generic content in the design decision making process at the system level.

2. The tool should map value generation from a design decision perspective.

3. The tool should record the options considered and the reasons why particular options were selected / rejected.

4. The tool should record three areas of support / influence:
    - People involved in decision making
    - IT used to support the process
    - Information sources consulted

5. In its implementation:
    - The tool should be flexible so that it can be used on live projects or retrospectively
    - User friendly and easy to understand
    - Not take too long to use

From problems encountered with data processing when investigating the change order request system, it was decided that an electronic data gathering tool could avoid some of the difficulties that arose. This was the author's recommendation

---

[5] The tool was originally designed to capture information about the briefing process, on the basis of identifying functional requirements and design parameters (Suh, 1990) as well as design decisions. However, due to limited time and resources within the research project it was not possible to explore both briefing and design decision making. It was intended that links be made between the two. With this constraint imposed upon the research it was deemed that the most important priority was to map the design decision making process. Therefore, the development of the briefing template in the EDGT will not be included in this thesis.

based on previous experience. However, the final decision rested with the potential users of the system.

6.4 TOOL DESIGN

Based on the findings from the interviews and using some terminology from Suh (1990), a template was constructed and shown to the project's industrial partners. The partners were invited to comment on the design of the template and their suggestions incorporated. This process had a number of iterations. The partners also commented on format, systematisation and implementation of the data gathering tool through a questionnaire.

6.4.1 Theory

The decision making template captures the decisions which are made to realise the client's requirements, as indicated by the briefing process, and information pertaining to the activities and reasoning involved in the decision making process. An issue of considerable importance regarding the value of this work is the type of design decisions which are recorded. The key factors in resolving this matter are the ability to add maximum value and effect the greatest cost reduction. It is on this basis that it was decided that the decisions which should be recorded should be those pertaining to the selection of systems for building attributes for each concept design.

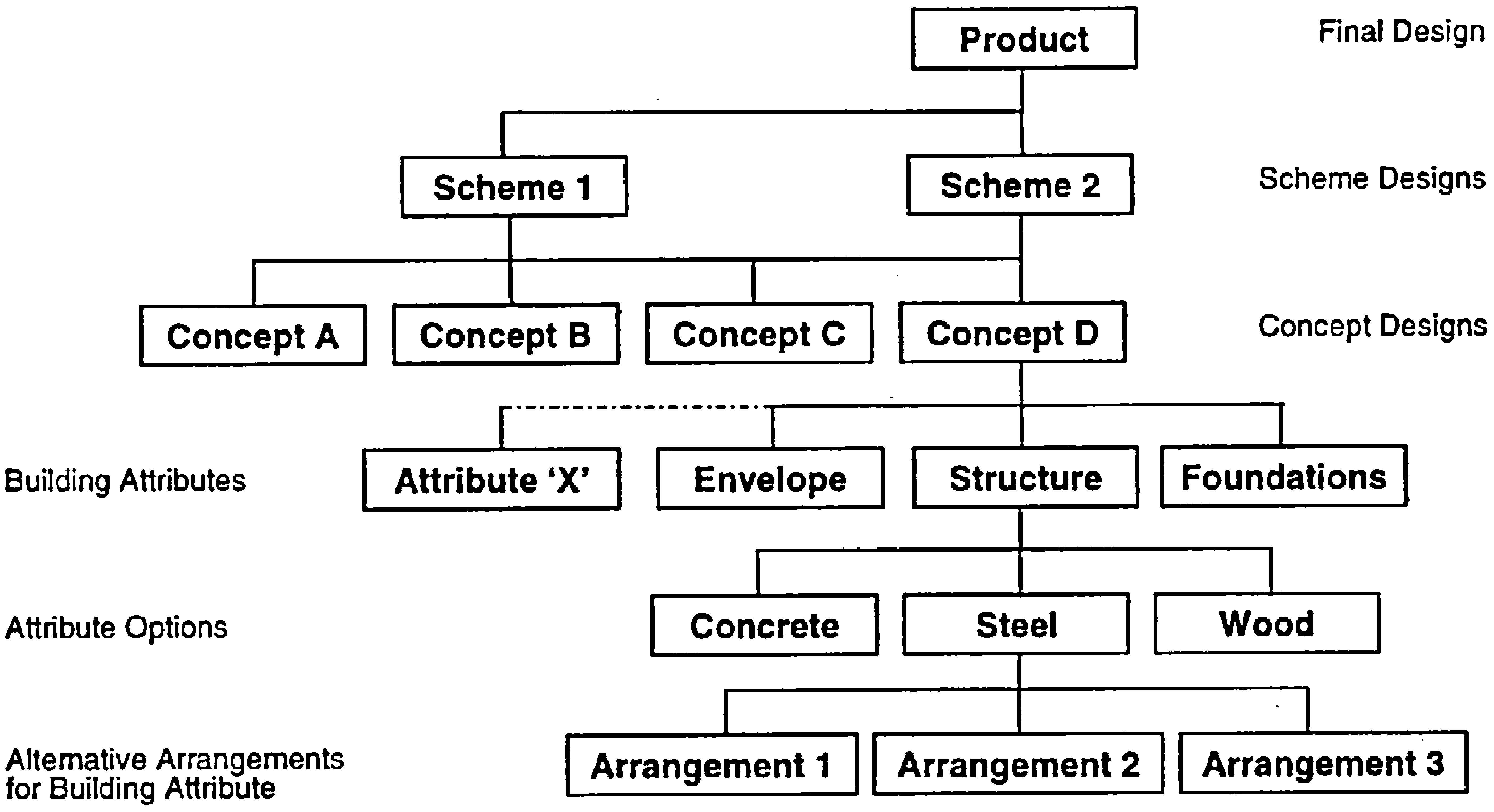


Figure 6.1 - Design decisions to be recorded by the data-gathering tool

Figure 6.1 shows the level of decisions of interest. Every building can be considered to consist of high level building *attributes* such as structure, foundations and external skin. Some of the attributes are generic to most, if not all, buildings whilst others will be project specific, depending upon the level of innovation of the design. When designing a particular concept a number of options are considered for any given attribute. The example in the diagram is structure with the options considered - concrete frame, steel frame and wooden frame. Also for each of those options, variations on a theme maybe considered - steel frame arrangement 1, steel frame arrangement 2...steel frame arrangement X[6]. The decisions of interest are those which choose between arrangements for a given option, and decisions which select options for a given attribute pertaining to a particular concept. This is for every attribute identified for every concept design produced. Also of interest are the decisions made to choose between concept designs to develop to scheme designs, and decisions made to choose between schemes leading to a final product. Therefore, for the purposes of this thesis, any future reference to the term ‘design decision(s)’ will be taken to mean design decisions at the *system* and *sub-system* level.

6.4.2 Information Fields

Each template records a single decision, the reasons for making it at a particular point in time and the issues which constrain the decision making process. Of particular interest are the options that are considered and the reasons why the particular options were thought to be suitable alternatives. The template captures which of the options was selected as the most appropriate solution, the reasoning behind the choice and, hence, the reasons for rejecting the alternatives. The template also records whether the decision has superseded / refined a previous decision. Information regarding the date the decision was made, the RIBA Stage at the time the decision was made and the identification of the person inputting the information is recorded. Process details are also captured: who made the decision, who else was involved, the level of agreement (imposed by the decision maker or consensus), type of meeting where decision was made and support in terms of IT and information sources. Table 6.1 shows all the information fields used together with an explanation of the data to be collected.

DECISION FACTORS	
Date the decision was made	This is the earliest date that a particular decision can be considered to have been taken. In other words, when there is no further debate or searching for alternative options relating to the decision made. Information type: date

---

[6] Depending upon how options / arrangements are considered, the two lowest tiers in Figure 6.1 could be combined (conceptually). For example, steel frame arrangement 1, steel frame arrangement 2, concrete frame 1, concrete frame arrangement 2, etc, could be considered as option 1, option 2, option 3, option 4, etc.

RIBA Stage	The RIBA stage that the project was in when the decision was made, is recorded. Information type: text
Decision made	A brief description of the decision which has been made is recorded in the form of a few words or phrases. Information type: text
Which decision has been refined / superseded (if any)	As part of the administrative aspects of recording data each decision is allocated a decision number. If a particular decision is a refinement or entirely supersedes a previous decision the number of the previous decision is recorded. This facilitates design iteration. Information type: number
Sufficient information available to make an informed decision	The person who completes the template is challenged to consider whether in his / her opinion there was sufficient information available to make an informed decision. This is a highly subjective information field that is aimed at identifying any decisions made in a particular project where the design team had to make an educated guess or take a risk to move the project along. Information type: yes / no *In practice this has limited use especially when the decision was made by somebody other than the person completing the template.*
Why was the decision made	A notes section to provide some background information as to why the decision was made at a particular point in time. In this section any issues arising which don't fit into any of the other information fields are recorded in the form of a number of phrases. Information type: text
Constraints impinging the design decision	These are the design issues which put boundaries on the design space. This includes technical issues, site constraints, client preferences, stipulations from the planning authority, other stakeholder views, building regulations, statutory authorities. Not only do constraints put boundaries on the design space but the unique mix of constraints with varying degrees of influence tend to drive the designer towards a particular solution. Information type: text
Options considered	A brief description of all the options considered for a particular decision are recorded.

	Information type: text
Reasons for considering options	For each option recorded above, reasons are cited for having considered it a suitable option in the first instance. So, out of all the possible solutions, or system choices, why was the 'options subset' considered worthy of further study. Information type: text
Option selected	The option that was selected from the options considered is recorded. Each option has an option number, the number pertaining to the option selected is noted. Information type: number
Reasons for selecting option	Given that a particular option has been chosen from the set of options considered, this information field records the reasons why a particular option was selected over the other options. Information type: text
Reasons for rejecting other options	Given that one option was selected from a set of options, the reasons why each of the remaining options were rejected is also recorded. Information type: text
Cost visibility (£s)	This information field records whether the designer had visibility of the cost implications when making a particular decision. Information type: pounds sterling *The intended figure was the difference between choosing one option over the other options but in practice figures from the cost plan were included where available. This means that most costing was retrospective and sometimes was a composite figure which included other aspects of the building than being recorded in a particular decision.*
Basis of cost visibility	Given that the designer says that he / she had visibility of the cost implications, this information field records the basis on which that figure was arrived at, e.g. quantity surveyor calculation, designer's calculation, guess, etc. Information type: text
Programme visibility (Wks)	This information field records whether the designer had visibility of the programme implications when making a particular decision. Information type: number of weeks

	The intended figure was the difference between choosing one option over the other options but in practice a figure was rarely given, although a few notes were provided on occasions relating to programme issues in the ***'Other knock on effects information field'****.*
Basis of programme visibility	Given that the designer says that he / she had visibility of the programme implications, this information field records the basis on which that figure was arrived at, e.g. planner's calculation, designer's calculation, guess, etc. Information type: text
Other knock on effects	Any other knock on effects of making the decision are recorded. Information type: text *Sometimes notes referring to the programme and cost were recorded here.*
PROCESS FACTORS	
Who made the decision	The person who actually made the final decision is recorded here. Information type: text *This can be quite difficult to identify at times. There was a tendency to want to cite the client as ultimately the client has to agree to any decision made by signing the design off, but this does not mean that the client has made the decision but rather that the client agrees that it is acceptable.*
Who else was involved in the decision making process	This identifies the other people who made a contribution to the design decision making process. Information type: text (yes / no) *This is in terms of people suggesting options or commenting in some way as to the suitability or effectiveness of options suggested by other people. People are characterised by their role such as quantity surveyor, structural engineer, client, architect, planning supervisor, etc. In the interests of speed, when systematised a list of roles was provided with tick boxes next to each role. The list of roles was compiled through a series of informal interviews with the industrial partners.*
Type of meeting	This is the type of meeting where the decision was made.

	Information: number *In practice a number of different types of meetings may have contributed to the decision making process but nevertheless an indication as to where each decision is finally made will give a first insight into the process of design decision making in construction projects. In practice the person completing the template could choose from a list of meeting types with the associated meeting type number being recorded. The list of meetings was compiled through a series of informal interviews with the industrial partners.*
Level of agreement	A subjective measure to gauge whether the decision was imposed by the decision maker or whether it was generally agreed that the option selected was the correct decision made. Information type: number *Based on a scale of 1 – 5.* *1 - represents that the option selected was imposed by the decision maker.* *5 - represents that all concerned were in agreement that the option selected was best suited for the decision being made.* *This is subjective as it is one persons opinion of the feelings of the rest of the design team. Again, it can only provide a first indication as to the nature of decision making and any analysis of these figures should be treated with some caution.*
Sources of information used in the decision making process	Records the types of information sources consulted to support the decision making process. Information type: text (yes / no) *In practice the person completing the template could choose from a list. An issue arose here with the level of detail to be included in the study, for example, if building regulations were consulted, is it sufficient to record 'building regulations' or should the particular aspect of the regulations used be recorded? It was decided that given the level of detail of the rest of this study that it would be sufficient to identify just 'building regulations' in the first instance. There was also a resource implication – it would take a great deal more effort to identify specific standards for each decision. The list of information sources was compiled through a series of informal interviews with the industrial partners.*
IT used to support the decision making process	Records the types of information technology used to support the decision making process. Information type: text (yes / no) *In practice the person completing the template could choose*

	from a list. The list of information technology types was compiled through a series of informal interviews with the industrial partners. Although the types of information technology used to support the decision making process are recorded, it in no way indicates how the tools were used. This means that it is not possible to assess how effectively tools were used but, rather, that they were employed in some capacity. This is in keeping with the level of detail of the rest of the study.
ADMINISTRATIVE ISSUES	
Project code	Project code referring to the case study - as supplied by partner companies. Helps identify project during data analysis phase. Information type: text
Project title	Project title referring to the case study - as supplied by partner companies. Helps identify project during data analysis phase. Information type: text
Date template completed	Date that a template recording a single decision was completed. Information type: date
Decision number	A number that uniquely identifies each decision recorded in the database. Helps with analysis. Information type: number
Who completed the template	The person completing the template – for identification purposes. Information type: text
Discipline	The discipline of the person completing the template. Information type: text
Company	The company of the person completing the template. Information type: text

Table 6.1 – Information fields used in the data gathering tool with explanations

6.4.3 Systematisation

To try to avoid previous difficulties at the analysis stage with the paper based change order data, it was deemed beneficial to systematise the tool into a software product. During the interviews with those likely to use the tool, the idea found a mixed reception with five architects in favour of a paper based approach and five in favour of a computer based tool (see appendix E page 17). Interestingly, this was a cultural split between the two architectural practices. The other important factor established through the discussions was the desire for the tool to take up the minimum amount of time and cause little disruption to normal working practices.

The decision making template was systematised using Microsoft Access 97™. The template consists of a number of forms with information fields which the user will input data. Where appropriate the tool has made use of *check boxes* and *drop down lists* to speed up data entry. The tool works on the basis that there will be one database per project. The program was selected because of its fitness for purpose and because of the partners' accessibility to the software.

A concern with this type of methodology is finding people who are able to find time to record data on a regular basis during a project to reap the medium to long-term benefits of research. The data gathering tool in its present configuration has gone someway to alleviate this problem by incorporating features which are useful to the practitioner in real time project management. For instance, the tool offers traceability of the decision making process and the reporting mechanism in Microsoft Access 97™ allows the user to produce relevant reports from the data which is being collected. The tool provides a method of tracking information transactions made between the user company and all other parties involved in the construction project. A report of outstanding information can be viewed to indicate which pieces of information need to be given further attention in terms of 'sending out', or have 'not yet been received'. This can be used to direct the user to information issues which require attention. Incorporated into the information transaction records are questions which will provide insights into the data sharing process. For each transaction the user is asked to specify how the information was requested, the medium in which the information was requested, and the medium in which the information was *actually* supplied. All of these functions were included to make the tool useful to the user and to encourage data collection. Another driver for companies to record information about the decision making process is to enable traceability for contractual reasons. The construction industry has a reputation for its adversarial nature (Rooke & Seymour, 1995) and companies want to protect themselves by keeping accurate information about the evolution of a building and events transpiring within a construction project.

6.5 USING THE ELECTRONIC DATA GATHERING TOOL

6.5.1 Implementation / Anticipated Use

The tool was used on three live construction projects (the details of which can be found in chapter 7) to capture information about the design decision making process. The design process is highly complex and requires the fusion of individuals' creativity through a number of interactions and exchanges and, as such, any prescriptive model has its limitations. However, these models are still useful to provide some insight into the mechanics of the process, not least of which is the RIBA model (1992), which provides a contractual view of the design process by splitting it into a number of design stages as follows: A-B - Inception / Feasibility, C - Outline Proposals, D - Scheme Design, E - Detail Design, F-G - Production Information and Bills of Quantities. The tool will be primarily used to record information from stage B through to stage E as indicated by this model. Although this is largely dependent upon when system level decisions are made and it is only in retrospect that it will be possible to say which stages were actually investigated. The data was recorded by partner companies which allows comparisons to be made vertically along the design process and horizontally at specific stages.

A user guide was produced that explained the functionality of the tool, details of how it was to be used and provided explanations for each of the terms. It was anticipated that the tool would be used throughout the design process as decisions were being made, although this was to be limited by the availability of projects and the degree of progress already made when the data gathering tool was introduced. The user, having identified that a system level decision had been made, would enter the data into the tool, completing all relevant information fields. For those decisions which had been made prior to the introduction of the tool a certain amount of retrospective data collection would be required. Each month the database was to be checked by the author to assess the quality of information being recorded. Visits would then be made on a bimonthly basis to talk through any issues that had arisen and to collect additional information to build a fuller picture of each of the case studies.

6.5.2 *'Actual'* Data Collection

Implementation of the tool proved to be more problematic than originally envisaged. The people recording the data, two architects and a planning supervisor, struggled to grasp what sort of information was needed for the research. This could be for a number of reasons. Firstly, the way the concepts were communicated. The author went through a learning curve which is likely to mean that his initial attempts at expressing the research objectives, terminology and methods were less effective in the early stages of data gathering. Secondly, the research method required the users of the tool to think in a particular way, which they were not used to. The author therefore underestimated the amount of time and effort required to *attune* the users to the research approach. Another problem was discipline. An issue of concern highlighted in section 6.4.3 was that the tool should be easy to use and take up as little time as possible. The tool failed to meet this objective as it takes approximately 20 minutes to complete one template. This was both a strength and a weakness. The design of the tool meant that it was possible to collect a considerable amount of detailed information about design decision making, although this was at the expense of the amount of time required to record the data. This factor, coupled with the issue of the users not being sure about what to document, led to a very slow start to the data gathering process. However, the situation was resolved by the author's offer to be present with the users on biweekly basis throughout the duration of the data collection period.

To facilitate the investigation a list *building attributes* was produced. This list is by no means exhaustive but was used to stimulate the user to identify the design decisions which had been made. The list is based on the physiology of buildings and has the assumption that if there are common characteristics to buildings then there is likely to be a common decision making process. The list used is as follows:

- Frame
- Substructure
- Roof Steelwork and Perimeter Columns
- Roofing
- Curtain Walling
- Doors
- Floors
- Parking
- Plant
- Blockwork / Partitions
- External Skin
- Architectural Metalwork
- Foot Print
- Electrical Services
- Fire Protection/Escape
- Ventilation
- Security
- Servicing (Vehicles)
- Mechanical Services
- Lifts
- Landscaping/Drainage
- Demolition
- Lighting
- Windows
- IT/Communications
- Sound Control
- Thermal Comfort

6.5.3 Data Gathering Tool Limitations

One of the limitations of the data gathering tool is that the data recorded only encapsulates one person's perspective of the process. Due to the amount of resource required to collect the data it was not possible to have multiple perspectives for each of the case studies. However, in a number of situations the users of the data gathering tool contacted other design team members and consulted project documents (drawings, minutes of meetings, etc.) to ensure the accuracy of the data being recorded. There was also a requirement that the person who was recording the data should have been actively involved in / close to the decision making process so that they would be aware of the issues involved in selecting a particular option, for example.

Another issue that arises is, to what extent does the tool represent the rationalisation of the designer / design team at the time the decision was made or the *post* rationalisation of the user when recording the decision for research purposes? By *post rational* the author means those arguments supporting the decision which are formulated *after* the decision was made. Post rationalising a decision may make it seem to have a more scientific basis than was really the case to reassure project stakeholders, or researchers. This issue is most likely to affect the information fields related to reasoning: reasons why options were considered and reasons for selecting / rejecting options. Design is not purely rational and the construction design process is impacted by issues other than technical, such as social and political expediency. It is the opinion of the author that, although this is likely to impact the study, it will not be a critical issue. This is because the tool is gathering information about decision making at the level of the 'interacting team'. A designer will often be asked to justify a decision or design recommendation by the client or another design team member. It is likely that such discussions are a mixture of the original rationalisation / analytical process of design, and a certain amount of post rationalisation when considering how to *present* the decision in the best light. Therefore, the post rationalisation phenomenon is present throughout the design process, and it is the author's opinion, that this is more likely to have an impact than additional thoughts at the data collection stage.

One of the limitations of the data gathering tool is that it does not address interdependencies between decisions. It was not intended that this tool should address interdependencies as well as all the other issues that are being investigated. This is an area for further work. Indeed, this has been considered in detail by Austin et al (1998).

The design of the data gathering tool was such that the users found it difficult to use alone. The complexity was not so much in the systematisation of the tool but rather in the adjustment that had to be made in the way that the users think and their understanding of what was required from the terminology used. Another important factor was the discipline that was needed to complete the template on a regular basis. Without sufficient encouragement, immediate work needs supersede the research agenda.

6.5.4 Improving the Electronic Data Gathering Tool

In hindsight, an additional feature to the data gathering tool could have been to ask the users to provide some indication as to the level of impact that a particular constraint had on the decision making process, e.g. (very important, important, medium, low impact, very low impact). This could also be applied to the different reasons that were recorded as to why a particular option was selected or rejected. In most cases several constraints and reasons were identified as impacting the decision making process, it is not always clear, however, which of these were the most important.

If the tool was to be used on a large number of projects for the purposes of producing a statistical sample, it would be necessary to radically reduce the number of information fields and simplify the tool. This would constitute a new research approach and would require considerable amount of thought to reconfigure the tool. The findings of this study may indicate issues which would be worthy of statistical study.

6.6 DISCUSSION

A data gathering tool was designed and systematised in Microsoft Access 97™ to map the design decision making process in construction projects. The tool was used on three live construction projects albeit with some degree of retrospective data collection.

The tool has been highly successful in terms of the amount and quality of data captured. The tool's main strength is that it records a significant amount of information pertaining to each individual system level decision. The data can be split into three broad areas: decision factors, process factors and administrative issues. The decision factors are those which relate directly to the decision such as specifying the decision, constraints, options and reasons for selecting / rejecting options. Process factors are those which relate to how the decision was made: who made the decision, who else was involved, what IT tools and information sources were used to help support the decision making process. Administrative issues are to do with identification of data to help at the analysis stage. The systematisation of the tool meant that the data was in the correct form to be analysed, although some manual data manipulation was required when matching decisions. These components of the data gathering tool template fulfil a number of the objectives identified in section 6.3.

The data collected facilitates the comparison of construction projects and allows a generic set of decisions to be identified. These decisions can be compared on the basis of time to see whether they were made in the same or similar order, and made at about the same time during the design period. However, there was the problem of how to identify equivalent decisions across projects. The issue is rooted in semantics. Each decision recorded was in the form of a few phrases or sentences to try to describe accurately what had been determined. The individual written style of the users often made identifying equivalent decisions a difficult process. The problem was eventually overcome by getting the users of the data gathering tool to match the decisions that they had recorded to the decisions recorded in the other case studies. A second issue that arose was the affects of semantics on the hierarchical nature of the decision making process. In some instances one decision in a particular project related to several decisions in another project. This becomes problematic at the analysis stage when comparing decision data. (Further discussion of this issue can be found in section 7.5.1).

The use of the EDGT on three live construction projects is presented in chapter 7.

[BLANK PAGE]

CHAPTER 7 MAPPING THE DESIGN DECISION MAKING PROCESS

"It [designing buildings] is very difficult to codify and to write down exactly what the factors are. It is a bit more vague and woolly and more of a synthesis than that. You really get all these points of view and all the technical requirements plus a bit of your own experience, you pinch a few ideas from somewhere else, and you chuck them all into a big pot and you stir it around and you warm it for three minutes." **Tim Quick, Sir Norman Foster and Partners.**

CHAPTER 7 MAPPING THE DESIGN DECISION MAKING PROCESS 139
7.1 INTRODUCTION 140
7.2 OBJECTIVES 140
7.3 CASE STUDY DESCRIPTIONS 141
7.4 DESIGN PLANNING 152
7.5 DATA PROCESSING 153
7.6 VALUE GENERATION: DECISION COMMONALITY AND CHRONOLOGY 155
7.7 DEFINING THE DISCIPLINES 163
7.8 WITHIN THE LIMITS: CONSTRAINTS & SELECTING DESIGN OPTIONS..... 167
7.9 COST & PROGRAMME VISIBILITY 174
7.10 WHERE DECISIONS WERE MADE 177
7.11 INFORMATION NEEDS / SOURCES 179
7.12 INFORMATION TECHNOLOGY SUPPORT 181
7.13 THE ROLE OF THE DESIGN MODEL 184
7.14 DISCUSSION 186
7.15 CONCLUSIONS 194
7.16 SUMMARY 196

7.1 INTRODUCTION

The Electronic Data Gathering Tool (EDGT), as described in chapter 6, was used on three live construction projects to gather data about the design decision making process at the system / sub-system level. The projects investigated were nominated by Stanley Bragg Partnership [SBP] and Taylor Woodrow Management Contracting [TWMC].

The three projects are:

1. Retail units – Chelmsford [SBP].
2. International departures lounge extension – Gatwick Airport [TWMC].
3. Supermarket – Bourne [SBP].

The case studies were selected mainly on the timing of, and accessibility to, current projects being undertaken by the industrial partners. The intended use of the EDGT was to install the software in the partner organisations and have data recorded by somebody involved in the design decision making process as the decisions were being made. This meant that the projects would have to be in the very earliest stages of development or, ideally, begin after the software had been installed. An additional constraint was that the time available for collecting data was approximately eight months and therefore all of the system / sub-system level design should be complete within that time frame. In reality, because of the discipline required to collect data, the tool was actually used more retrospectively than currently, albeit within the context of on going projects. This meant that the design period could be longer than eight months as long as data collection was possible within this duration.

7.2 OBJECTIVES

The objectives of mapping the design decision making process are as follows:

1. Identifying potential for standardising work – based on the generic content of the design decision process.

2. Map value generation from a design decision perspective.

3. Develop insights into:
   - The role of each discipline
   - Cost / programme visibility of designers
   - Constraints and reason drivers
   - Information sources used
   - Information technology used

The first two objectives relate directly to the implementation of lean thinking (see section 6.2.4). The list of decisions for each case study can be thought of as representing a subset of the 'value stream' maps (see section 2.2.2.2). That is, the subset which directly adds value to the product. The design decision is the means of 'value generation' of the product development process and therefore the list of design decisions, and associated information, can be thought of as 'value generation maps'. It is important to distinguish between the actual decision and the means by which that decision is made. The aim of the decision making process is to make the best, most informed design decision within a given set of constraints. The process itself is made up of a number of tasks which seek to identify and test those constraints. For any particular decision this process can be performed in a number of ways, some being more wasteful than others. If value stream maps were to be produced they would identify each of the tasks performed and then categorise them into either:

1. Tasks which unambiguously add direct value to the product.
2. Tasks which add no value to the product but are unavoidable with current technological limitations of the production processes / technologies.
3. Tasks which add no value to the product and are immediately avoidable.

The value generation maps represent the value adding activities and therefore 'leanest' approach to design. This does not, however, indicate what process route should be taken to minimise waste when making a particular decision. It could be possible to produce value stream maps for each particular decision with the decision being considered as the 'product'. This would help optimise the design process by removing any unnecessary tasks. However, for the purposes of this study, only the system / sub-system value generation maps will be produced. The decisions that have to be made are based on the building attributes required and should therefore encapsulate the client's requirements.

The third objective is to gain insights into various aspects of the design decision making process which may lead to suggestions as to how the design process can be made more efficient and, hence, 'leaner'.

7.3 CASE STUDY DESCRIPTIONS

For the purposes of brevity each of the case studies will be referred to by the place where they are located.

7.3.1 Chelmsford

The Chelmsford High Street case study is a development of two 'multiple high street units' in Chelmsford town centre. The project came about in an informal manner. The architect was contacted by the developer and asked to make some suggestions for commercial development of the site in Chelmsford. This constituted the initial project brief, thus providing the designers with a significant degree of freedom. The task was fulfilled by producing a number of sketch plans showing alternative arrangements of retail units on site. This service was performed by the architect in good faith, such that, having put time and energy into the project, when the contract was placed they were chosen as the architectural practice to 'complete' the scheme's design. The developer is remote from the design team, having plan sketches sent to him for evaluation. One particular arrangement was considered suitable by the developer who then organised funding for the scheme. The inception of the project was in November 1996 and the budget was later fixed at £1.475 million for $3000m^2$ of new build retail space: 2 buildings each of two storeys, of approximately equal size. This budget only includes the shell and core of the new build, additional money will be spent by tenants on fitout.

The scheme was procured in a traditional manner, however, the developer decided to compress design time to try to begin construction as early as possible. This led to a considerable overlapping of the different design stages as defined by RIBA (1992). Another issue that affected the development of the scheme was that tenants were only found late on in the process. This meant that a lot of the tenants' needs were assumed on the basis of professional experience and market knowledge. It also meant that the scheme had to go to planning for a second time to accommodate changes that one of the tenants required. The project team can be seen in table 7.1.

Chelmsford Design Team	
Discipline	**Company**
Architect	Stanley Bragg Partnership Limited
Architect (A) (Senior)	Stanley Bragg Partnership Limited
Architect (B) (Technician)	Stanley Bragg Partnership Limited
Client (Developer)	Shearer Property Group
Client (Developer – B)	Shearer Property Group
Contractor	Hutton Construction
Funders	Morgan Grenfell Asset Management Ltd
Letting Agents	Awbery Lapsa
Local Authority - Planning Officer	Chelmsford Borough Council
Local Authority - Case Officer	Chelmsford Borough Council
Party Wall Surveyor	Keith Douglas Partnership
Planning Supervisor	Rowney Sharman
Project Manager	Rowney Sharman
Quantity Surveyor	Murdoch Green
Structural Engineer	Harris & Sutherland

Table 7.1 – Design Team (Chelmsford)

The site had a number of constraints. Firstly, the High Street shop frontage was a grade II listed building which had to be retained. This meant that the project would consist of some 'new build' and refurbishing work (the budget also includes the refurbishment of the listed building). From the beginning there was contact with the planning authority, especially with regard to the listed building. The site was of keen interest to the planning authority because of the historical importance of the existing buildings and the central location of the site. Running through the site was a public right of way, which had potential planning implications if diverted or removed. Another issue related to the adjacent property owners. It was hoped that the adjacent properties could be incorporated into the scheme, however, the owners decided not to partake in the development, there by, delineating the site boundary.

A detailed survey of the site found that some areas were contaminated because of former activities, and that the water table was very high.

7.3.2 Gatwick

The Gatwick project is an extension to the International Departures Lounge (IDL) at the South Terminal, Gatwick Airport. The project was commissioned by the British Airports Authority (BAA) as a means of coping with the increase in passenger numbers expected in the next few years. The inception date of the project is not known as the decision to build was part of the internal decision making process of the client body. The need for the scheme comes out of the BAA master plan which forecasts future needs at the airport based on recent trends. However, the feasibility study for the scheme started in February 1998. The budget for the project is £16.5 million – reduced from £20 million with cost saving measures. Interestingly, this project is also an Egan demonstration project, i.e. a project that is striving to apply some of the principles outlined in the Construction Task Force's paper, Rethinking Construction (1998).

The project comprises a mixture of retail and airport operational areas. There is a desire to maximise the amount of retail space available to maximise revenues whilst not compromising operational functions. In addition to the finished product, the construction phase of the project must aim to minimise the effect on current operations, taking in to account Health & Safety and security issues.

Table 7.2 shows the design team for the Gatwick project. BAA is unusual in that it operates a partnering framework agreement. The framework covers most of the major design disciplines such as architects, services engineers, structural engineers, project managers, contractors and some sub-contractors. This means those companies who are involved in the project are available to provide input to the design process from the outset. It also means that suppliers for materials should also be selected from within the framework whenever possible. Another peculiarity to this project is that it operates under the BAA design stages rather than the RIBA stages (see section 3.2). The BAA process is far more proactive in its approach to controlling the design process which means that the design team have to follow the stages more prescriptively[7]. The design team was only contracted to do design work up until the end of 'co-ordinated design' – BAA

---

[7] At one stage of the project the design team challenged the BAA process as it would have held up the design process if adhered to rigidly. Permission was given by the client body to proceed with the desired schedule.

process stage D, framework suppliers were contracted to provide all the production drawings.

Gatwick Design Team	
Discipline	**Company**
Architect	Geoffery Reid Associates
Architect	Fitch
Client	BAA
Client - Project Board (BAA)	Gatwick Airport
Construction Manager	Taylor Woodrow Construction
Framework Contractor	Rowen Structures Limited
Framework Contractor	Van Dam UK Limited
Framework Contractor	O'Rouke
Framework Contractor	Crown House Engineering
Planning Manager	Taylor Woodrow Management Contracting
Planning Supervisor	WS Atkins
Project Manager (BAA)	BAA
Project Manager - Fitout Contractor	TCL
Cost Stylist (QS)	EC Harris
Retail Design Consultant	Fitch
Service Engineer	WSP
Structural Engineer	HJT

Table 7.2 – Design Team (Gatwick)

7.3.3 Bourne

The Bourne project is a 2356m^2 (25,000ft^2) country town supermarket scheme. The developer initiated the project in March 1996 by requesting the architect produce a design for a supermarket which would fit onto the Bourne site, that could achieve outline planning, and then be offered to prospective customers. The developer had a specific client in mind and, hence, the supermarket was designed to a particular specification. This specification was written into a legally binding contract. The site was not bought by the 'target' client but rather by JS Sainsbury. JS Sainsbury's standard store configuration is somewhat different to the scheme that they had bought into and, therefore substantial design changes had to be made. This meant that the project consisted of two distinct design phases. The first was on behalf of the developer to produce a design that could be marketed effectively and the second was on behalf of JS Sainsbury, the ultimate client. When JS Sainsbury bought the scheme they hired a contractor under a design and build contract to procure the building. The contractor novated the architect to complete the design of the supermarket. Table 7.3 shows the project design team.

The core design team had worked together on a very similar project prior to the Bourne scheme, under similar contractual conditions. Hence, the design adopted for the site was very similar to the previous project. Indeed, the plan of the first building was taken and positioned onto the Bourne site, with some adjustment to account for site constraints. Also, JS Sainsbury had decided that the design of this particular scheme was to become its standard 'country town store' configuration. This meant that all the design information produced was recorded by JS Sainsbury and stored in a database for future use. Unlike the Chelmsford project, the design of the supermarket is heavily constrained by the client through the use of client organisation design guides.

Bourne Design Team	
Discipline	**Company**
Acoustic Engineer	Lee Cunningham Partnership
Architect	Stanley Bragg Partnership
Architect (Fit Out)	Hadfield Cawkwell Davidson
Civil Engineer	White Young Green
Client	J Sainsbury
Client's Agent (QS)	Henry Riley & Son
Contractor (Project Manager)	RG Carter
Contractor's QS	BDB
Developer	Carter Commercial
Developers Agent (QS)	Dickson Powell
Highways Engineer	Flynn and Rothwell
Legal Advisor	McGuinness Finch
Party Wall Surveyor	GL Hearn
Planning Adviser to Sainsbury	Town Planning Consultants
Planning Officer	South Kesteven District Council
Public Relations for Client	Greylink
Refrigeration	Oaksmere
Services Engineer	Roberts & Partners
Steel Sub Contractor	TSI
Structural Engineer	White Young Green

Table 7.3 – Design Team (Bourne)

During the project there were two significant periods, approximately 6 months long, when no design work was undertaken. The first was from October 1997 until March 1998. This was because the client's internal decision making body had issues to reconcile before continuing with the project. The second delay ran from May 1998 until October 1998 and was caused by the design and construction of a building for the original owner of the site. Part of the Bourne scheme required the relocation of the original site owner. Because of the delays, the rest of the programme was considered to be tight. The budget for the project was £1.5 million for the shell and highways. The client's fitout budget was £1.2 million.

7.3.4 Comparison

A comparison of the case studies has been made. The following characteristics have been contrasted:

- Client experience
- Design management contract
- Design stages
- When each discipline joined the design team
- Comparison of building attributes, including construction contracts
- Design features of each building

	Chelmsford	Gatwick	Bourne
Client Experience	High	High	High
Level Of Client Sophistication	High	High	High
Client Procured This Type Of Building Before?	Yes	Yes	Yes
Details	Multiple, 7 ongoing, 10s previously	One finished five years ago, a similar building at North Terminal	Multiple
Repeat Client?	Yes	Yes	Yes
How Many Projects Done With Them Before?	2	10s within last ten years	Multiple till feasibility, not many completed buildings
What Design Management Contract Was Used?	RIBA – slight variation	BAA Framework Agreement	Flat fee for feasibility studies - developer to sell site
Budget	£1.475 million – Shell and Core	Originally £20 million, with cost saving measures: £16.5 million	£1.5 million – Shell and Core £1.19 million - Fitout
Site Pre-Selected?	Yes	Yes	Yes

Table 7.4 – Client Assessment for the Case Studies Used in Design Decision Process Maps

Table 7.4 shows the data collectors' opinions of the experience of the clients in each of the projects. All of the clients were considered to be very experienced in the procurement of buildings, even in the specific type of building that was the subject of each project. Not only were they considered to be experienced professionals, but they were also considered to be highly competent people who had dealt with the designers on previous occasions. The design management contract for each of the projects were somewhat different, Chelmsford – a slight variation on the RIBA contract, Gatwick – part of the BAA framework agreement and Bourne a flat fee for feasibility work. For both Chelmsford and Bourne a considerable amount of design work is conducted without a formal design contract on the understanding that, if the projects are to proceed, they will be contracted as the designer for the scheme. In all cases the site was pre-selected.

Table 7.5 shows the start and end dates of each of the design stages. It also shows the date when the construction contract was placed and the dates when schemes achieved planning. Interestingly, the RIBA stages as used for the Chelmsford and Bourne project seemed to have little or no impact on the way in which the design work was conducted. The designers' only had a vague awareness of what constituted each design stage. The RIBA approach did, however, offer a means of defining project milestones. The dates in table 7.5 also show that there was considerable overlapping of some the stages for both projects. This is because there was a tight schedule in each case. For both of these projects the RIBA stages do not represent controlled stages which are to be adhered to before moving to the next stage, but are merely a means of assessing what sorts of activities should be done within a particular time period. For the Gatwick project the BAA stages had a much more significant controlling effect. With particular requirements having to be fulfilled before moving onto the next stage.

The inception of the Gatwick project was largely incorporated into the internal decision making process of the client body. The need for the project came about through forecasting future needs at the airport in the BAA master plan. The design team was employed from feasibility onwards to meet the predicted requirements.

	Chelmsford	Gatwick	Bourne
Date of inception	23/11/96	Start of Feasibility 12/2/98	1/3/96
Date of placing the contract	15/3/99	D_2 Day (Equivalent) 25/11/98	5/11/98
Stage A-B	23/11/96 –15/9/97	Inception is an internal client process (Feasibility) 12/2/98 – 5/5/98	1/3/96 – 6/10/97
Stage C	5/7/97 – 5/2/98	5/5/98 – 26/8/98	4/9/96 – 6/10/97 End User *4/3/98 – 4/5/98
Stage D	5/7/97 – 5/2/98	26/8/98 – D_1 Day 16/9/98 D_2 Day – 25/11/98	3/5/97 - 6/10/97 End User **30/10/98 – 23/12/98
Stage E	5/11/97 – 5/2/98		2/9/98 – 4/12/98
Stage F	5/11/97 – 23/4/98		2/9/98 – On going
Stage G	5/5/98 – On going		2/9/98 – On going
Outline Planning			6/10/97
Detailed Planning	23/11/97	July / August 1999	
Planning for Reserved Matters			30/10/98 Also resubmissions for minor changes to scheme

Table 7.5 – Design Stage Dates for the Case Studies Used in Design Decision Process Maps

Table 7.6 shows when each member of the Chelmsford project joined the design team. It clearly shows that the majority of the early design work was carried out by the architect in conjunction with the client's supporting advisors. The other principle designer, the structural engineer, was not appointed until approximately one third of the way through the design process. Interestingly, a services engineer was not required on this project. This is because the services aspect of the building was considered to be sufficiently simple as to be carried out by the project team in the absence of a qualified services engineer.

Discipline	Joined Project Team	
	Date	Normalised Time
Client	23/11/96	0
Architect	23/11/96	0
Structural Engineer	15/9/97	0.334096
Legal Advisor	23/11/96	0
Project Manager	15/9/97	0.334096
Quantity Surveyor	23/11/96	0
Client's Agent	23/11/96	0

Table 7.6 – When Design Team Members Joined the Project (Chelmsford)

The project team for Gatwick was appointed under the BAA framework agreement (partnership arrangement) at the beginning of feasibility. This means that all disciplines were available to make contributions to the design process from the very earliest stages.

Table 7.7 shows when each discipline joined the design team for the Bourne project. The project essentially comprised of two design processes, or design phases, the first for the developer and the second for the end user. The delay between inception and the appointment of the disciplines in the first design stage represents the period of the developer's internal decision making process. Similarly to the Chelmsford project, the majority of design in the early stages of the first phase was conducted by the architect. The second phase began with the sale of the site to the end user, JS Sainsbury. JS Sainsbury employed a contractor under a design and build contract, who in turn employed the other design specialists. This took place at about 60% of the total design process (both phases). Only the refrigeration consultant was appointed to the team at a later date to assist with fitout items.

Discipline	Joined Project Team	
First Design Stage – Developers Design		
	Date	**Normalised Time**
Client (Developer)	1/9/96	0.148637
Architect (SB)	1/9/96	0.148637
Highways Engineer	1/9/96	0.148637
Legal Advisor	1/9/96	0.148637
Planning Consultant	1/9/96	0.148637
Quantity Surveyor (Developer)	1/9/96	0.148637
Site Finder (Developer)	1/9/96	0.148637
Acoustic Consultant	1/11/96	0.198183
Second Design Phase – End Users Design		
	Date	**Normalised Time**
End User (Client – Sainsbury)	1/3/98	0.59455
Architect (Shell – SB)	1/3/98	0.59455
Structural Engineer	1/3/98	0.59455
M & E Services	1/3/98	0.59455
Fitout Architect	1/3/98	0.59455
Refrigeration	3/10/98	0.769612
Contractor	1/3/98	0.59455
Quantity Surveyor (Sainsbury)	1/3/98	0.59455
Quantity Surveyor (Developer)	1/3/98	0.59455

Table 7.7 – When Design Team Members Joined the Project (Bourne)

Table 7.8 shows a comparison of the building attributes for each project. All three projects have a new build component. Chelmsford has two, two storey, 'multiple retail units' with a total floor area of 3000m^2. Gatwick has a similar sized facility although it is an extension to an existing building and the floor area is spread over five storeys. Bourne is a single storey construction of 2,356m^2. Chelmsford also has some refurbishment work within a grade II listed building. All three buildings

Building Details

Name of Building		**15 - 18 High Street Chelmsford**	**South Terminal IDL Gatwick**	**Exeter Street Bourne**
Project Type		Refurbishment / Construction	Extension of existing facility	Construction
Building Type		Retail	Retail/operational areas (sitting, transfers)	Supermarket
Location		Chelmsford, Essex	Gatwick Airport	Bourne, Lincolnshire
Floor Area		3000 m^2	3066m^2	2356m^2
Height		12m	20m	7.5m
No. of Storeys		2	5	1
Type of Construction	**Brick**	Yes		Yes
	Steel Frame	Yes	Yes	Yes
	Concrete Frame			Concrete around some of steel frame
	Cladding		Yes - steel panel with glass	
	Roof Type	Slate	Aluminium sheet roof	Profile steel
	Distinctive Features	Retained Listed Building Range		Main entrance

Construction Planning

Type of Contract		JCT 80 Measured with Quantities	BAA specific based on New Engineering Contract - multi contractor version (with suppliers)	Design and Build
Length of Phase	**Planned Construction**	9 months	22 months	6 months
	Pre-eng.	Steel frame components fabricated off site during contract	Pre-formed service modules - piping, duct work, cables	Steel frame (arrives on site as a kit ready for construction) Windows - units made up railing features for boundary wall, all the soffits, eaves, and faciaes for roof prefabricated, painted off site
No. of Contractors		1 main contractor, 4 subcontractors		1 main contractor, 20 subcontractors
No. of Work Packages		5		17

Table 7.8 – Building Details and Construction Planning Outline for the Case Studies Used in Design Decision Process Maps

are used for different functions, although there is a common retail theme. Chelmsford has two high street retail units, Gatwick an extension to of the IDL comprising retail areas, public spaces and operational facilities, and Bourne is a supermarket store. The production phase of each project was contracted in a different manner: Chelmsford – JCT 80 with measured quantities, Gatwick – BAA framework agreement, based on New Engineering Contract and Bourne – Design & Build. Each building has a steel frame and two of the buildings use brick as the external skin, with Gatwick using a cladding system. The planned construction durations range from 6 to 22 months.

Design Features

Name of Building		15 - 18 High Street	South Terminal IDL	Exeter Street Bourne
Level of Innovation	Design	Medium	Medium	Medium
	Materials	Low	High	Medium
	Assembly	Low	High	Medium
			High - people on board, contributions to design, programme and cost implications, process mapping - selections made on basis of cost and programme after function	
Level of Architect Output from CAD to Main Contractor		High 80 %		Medium ~ 60% General Arrangements, production drawings, site layout and elevations, done on CAD Majority of design details are hand drawn

Table 7.9 – Design Features for the Case Studies Used in Design Decision Process Maps

Table 7.9 shows how the projects compare in terms of design innovation. Chelmsford and Bourne are considered in the medium and medium – low brackets in terms of design, materials and assembly. Gatwick is considered as being high in terms of materials and assembly because of the early inclusion of manufacturing knowledge from suppliers.

7.4 DESIGN PLANNING

One of the biggest problems of construction design is the lack of design planning (Coles, 1990). In his study Coles states there is a certain amount of disbelief amongst designers that effective design planning is possible. This still appears to be the situation nearly a decade later as, for two of the three case studies, design planning is little more than a Gantt chart outlining the timing of each of the main activities for each of the design stages. The Gatwick case study was unusual in that a considerable amount of effort had been put into planning the design process. A process map of each design stage was produced outlining the major tasks that had to be completed. The map was split into sections relating to different building / project characteristics, such as mechanical design, escape strategy, foundations, frame, surveys and management controls – 33 in all for stage C BAA design process. Within each of these sections there were multiple tasks, each demonstrating interdependencies. Interdependencies also linked tasks in different sections, i.e. task groupings did not necessarily reflect tasks which could be done in parallel and in isolation from each other.

Another concept which was introduced in this approach was the idea of design 'fixities'. Once a decision had been made about a particular system / design option, this was 'fixed' and all design tasks that are dependent upon this decision can move forward with confidence that the input information will not change. After a fixity had been established, 'fixity sheets' outlining the decision taken were released to each of the design team members as a means of communicating the decision to the team. This idea of freezing the design in itself is not an entirely new concept. What appears to be novel, however, is the idea of formally freezing different aspects of the design early on in the process to help progress other design tasks. The construction design process can be considered as being analogous to 'crystallisation'. This approach of design fixity is a controlled, and perhaps an accelerated, crystallisation process. The Gatwick case study also had a stated policy of using standardised components and design rationalisation wherever possible. The other projects had no equivalent approach. Interestingly, Baldwin et al (1999) also use this term with regard to the use of Design Structure Matrix (DSM), to focus the deign manager's attention where 'fixity' is needed to avoid design changes and abortive work.

7.5 DATA PROCESSING

Data was collected in the form of tables for each case study. The main table for each project consisted of 132 information fields and from 83 – 98 records, 1 for each system / sub-system level decision recorded. Table 7.10 shows the disciplines that were involved in the data collection process. Each of the people collecting data were involved in, or close to, the design decision making process.

Case Study	Discipline	Company
Chelmsford	Architect	Stanley Bragg Partnership
Gatwick	Planning Manager	Taylor Woodrow Management Contracting
Bourne	Architect	Stanley Bragg Partnership

Table 7.10 – Disciplines' of the Data Collectors

7.5.1 Matching Data

One of the most important data processing issues for this study was identifying which of the design decisions were 'equivalent' across case studies. Some were quite easy to establish, for example, the choice of material for the frame. Others were far more difficult, however, because of semantics. Each of the data collectors had their own style for phrasing the decisions that had been made. This meant that there was not necessarily an obvious correlation between two equivalent decisions. Semantics also led to a hierarchical problem being introduced. That is, one decision in one case study was equivalent to two or more decisions in another case study.

For the purposes of establishing equivalence between design decisions across case studies, each of the data collectors was asked to match his decisions to the decisions made in the other case studies. This worked surprisingly well as all data collectors reinforced each other's decision matching, with only a few discrepancies. Having overcome the problem of matching decisions, the second issue of design hierarchy had still to be addressed. The hierarchical nature of the decisions was only a problem with respect to processing the data. The three sets of data were matched as three pairs: Chelmsford – Gatwick, Chelmsford – Bourne and Gatwick – Bourne. Where, for example, one Chelmsford decision was equivalent to three Gatwick decisions, two additional, identical, records were created for the Chelmsford case study, with each of the three Gatwick decisions being matched to one of them.

Data was transferred from MS Access 97™ to MS Excel 97™ for the purposes of data processing. The following is a list of the types of graphs that were produced for each case study:

- Matched design decisions against normalised time
- Cumulative count of design decisions made against normalised time
- Distribution of design decisions (groups of 0.1 normalised time)
- Distribution of design decisions (groups of 0.05 normalised time)
- Who Made the design decisions
- Percentage of design decisions in which the design team members played an active role
- Percentage of design decisions particular constraint categories as impinging upon the design process
- Percentage of design decisions using particular reason categories to choose between options
- Designer's cost visibility
- The types of meetings where design decisions were made
- Percentage of design decisions using particular information source types
- Percentage of design decisions using particular information technology types
- Percentage of design decisions occurring in each RIBA stage

The following is a list of the types of tables produced from the data for each case study:

- List of system / sub-system level design decisions in order of decision occurrence
- List of system / sub-system level design decisions in order of decision maker (defining decision maker roles)
- List of system / sub-system level design decisions that the various disciplines were involved in making (defining decision assistance roles – a table for each discipline)
- List of system / sub-system level design decisions with corresponding constraint and reasons for selection categories
- Information needs

A comprehensive set of graphs and tables can be found in appendices G, H and I.

7.5.2 Decisions Superseded

In both the Chelmsford and the Gatwick case studies some decisions were superseded by later decisions. This is indicative of design iteration. The tool did not seek to investigate this phenomenon in detail, however, therefore a number of iterations may have occurred before some of the decisions were finalised. It is this finalised decision in most instances which the EDGT captures, which means that most iterations were not recorded. Any decisions which have been superseded in the tables that follow, and the tables in appendices G – I, are highlighted in bold text.

7.5.3 The Design Period

For the purposes of producing normalised time graphs the 'design period' had to be defined. A suggestion was made by one of the industrial partners that the design period should run from inception to the date that the contract is placed. Because of the different contractual arrangements for each project, BAA framework, design and build and a more traditional procurement route, this led to distortions in the data. Therefore the author has defined the design period as 0 – representing the 'inception of the project' and 1 – representing the 'date that the last system / sub-system level design decision was made'. The only exception is for Gatwick. Because work was performed on the Gatwick project as part of the internal decision making process of the client body, the design period for this case study is defined as 0 – representing the start of 'feasibility' and 1 - representing the 'date that the last system / sub-system level design decision was made'.

7.6 VALUE GENERATION: DECISION COMMONALITY AND CHRONOLOGY

Matching equivalent decisions between projects allowed an assessment to be made of the amount of commonality that exists in the design decision making process in construction projects. The generic content between each pair of case studies was found to be between 73% - 80%, at the system / sub-system level. This is an important finding as it contradicts the commonly held assumption of the uniqueness of each construction project. This statement is not without qualification, however, as the detail of each project is specific to each design, but the importance of the finding resides in the knowledge that whatever project is to be undertaken 73% - 80% of the *types* of decisions that have to be made are the same. This means that planning design in greater detail is achievable and likely to lead to a more regular approach to design.

Figure 7.1 shows the cumulative count of system / sub-system level design decisions made for each of the three projects. Each graph shows only the incidence of when a decision was made and makes no attempt to reconcile *what* decisions were made. The graph shows a remarkably similar trend between the three projects. The shapes of the graphs demonstrate the characteristic 'S' curve. All three case studies had very slow starts, with less than 5% of the design decisions made by 20% of the total design period. Between the curves there are quite larger tolerances, for instance at approximately 50% of the design period the Chelmsford project has made approximately 40% of the design decisions whereas the Bourne project has made approximately 60% of the design decisions. Interestingly there are a number of crossing points which illustrate that a particular project does not always 'lead the way'.

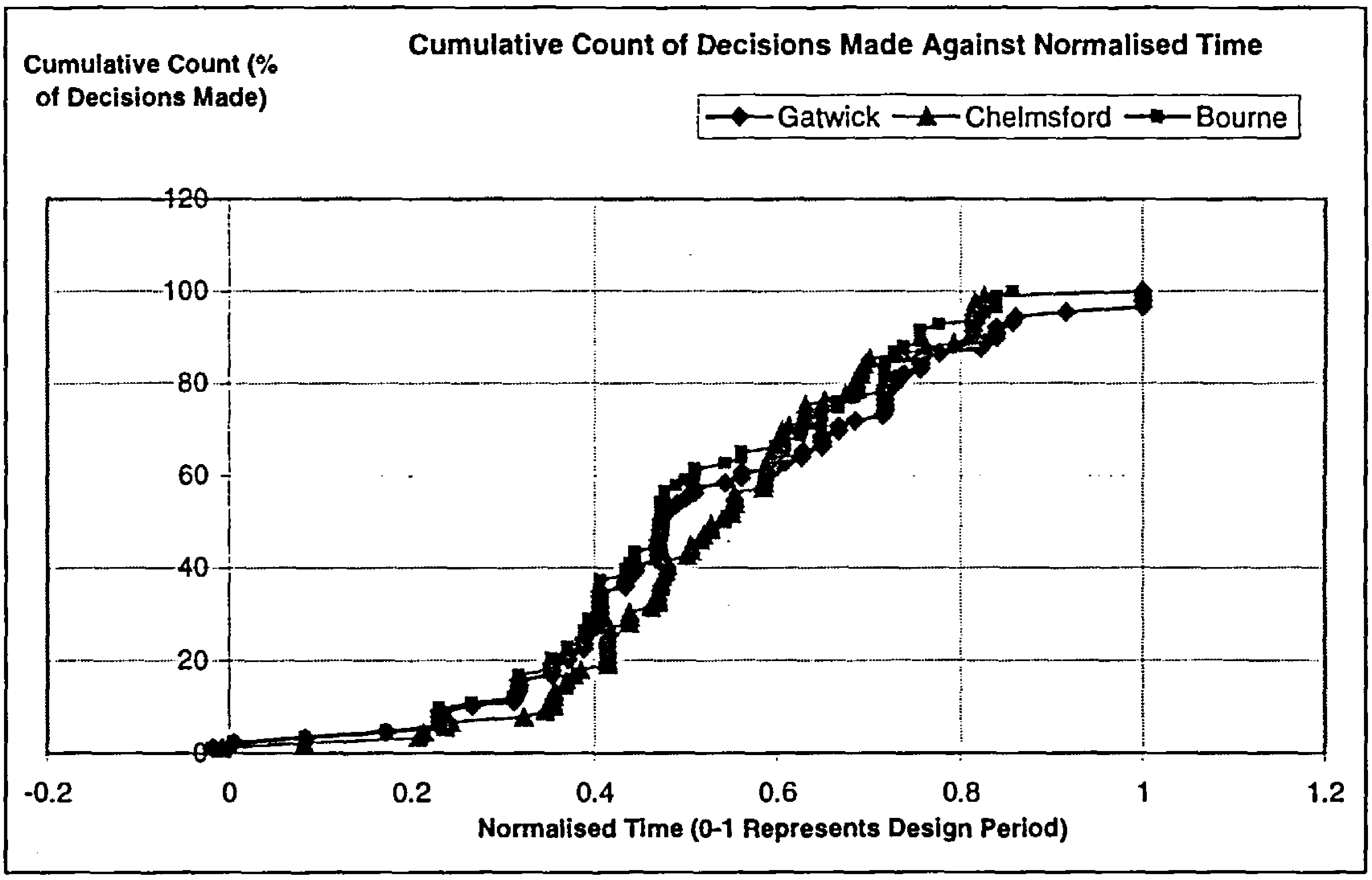


Figure 7.1 – Cumulative Count of Decisions Made Against Normalised Time (all three case studies)

Figures 7.2 – 7.4 show the distributions of when decisions were made against normalised time (groups of 0.1 normalised time). These graphs can be compared with figure 7.1 to illustrate more fully the incidence of design decision making. Figure 7.4 shows that Bourne is different from the other two case studies. This is largely due to the fact that two design phases took place in the Bourne project: the developer's design and the end user's design. There were also two periods of approximately six months were little work was done on the design of the supermarket. The first related to issues which had to be reconciled within the end user organisation and the other delay was caused by the design and construction of a building for the original owner of the site. The original owner of the site was to be relocated within the terms of the sale. The Chelmsford and Gatwick projects display similar characteristics. Very few decisions made in the first 20% of the design period and rising to a peak at approximately 50% of the design period, where nearly 60% of the decisions have been made. Interestingly, both peaks tie in with an end of stage: RIBA - C,D,E for Chelmsford and BAA - stage C for Gatwick. Following each peak is a tail off of the number of decisions made. The Gatwick graph falls sharply by the 60% point of the design period and Chelmsford somewhat more gradually until the 80% point of the design period. Further insights into this phenomenon can be gained by considering figure G.3 in appendix G and figure H.3 in appendix H. These graphs show the distribution of decisions made against normalised time, with groupings of 0.05 normalised time. In figure G.3 it can be seen that the system / sub-system design effort remains relatively constant until the 75% point of the design period. By this time approximately 85% of the design decisions have been made. There is an interesting spike of activity at the 85% point of the design period. Figure H.3 shows that, although the design effort tailed off dramatically in the Gatwick project, it remains relatively consistent, albeit at a lower level of activity.

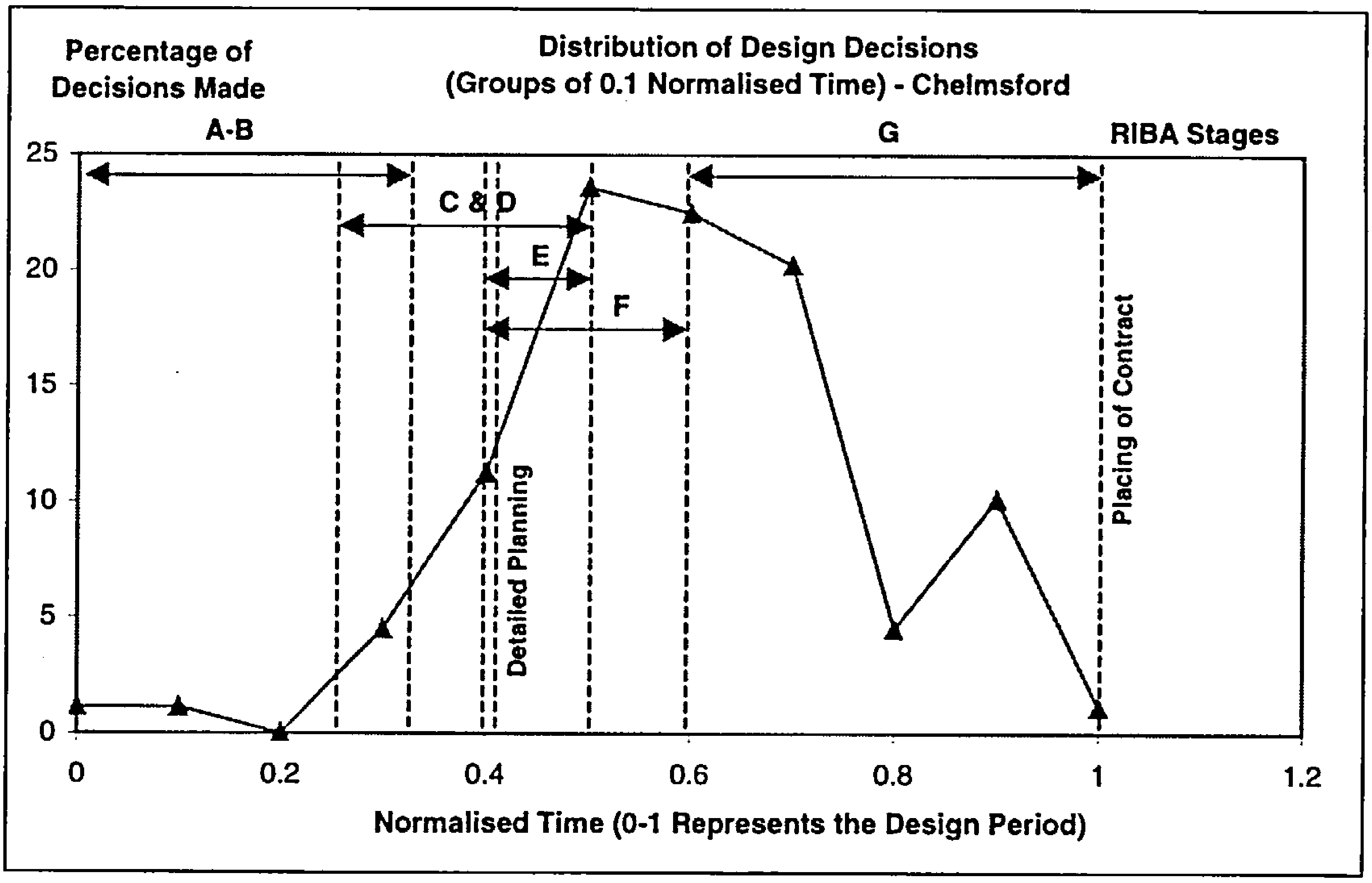


Figure 7.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) – Chelmsford

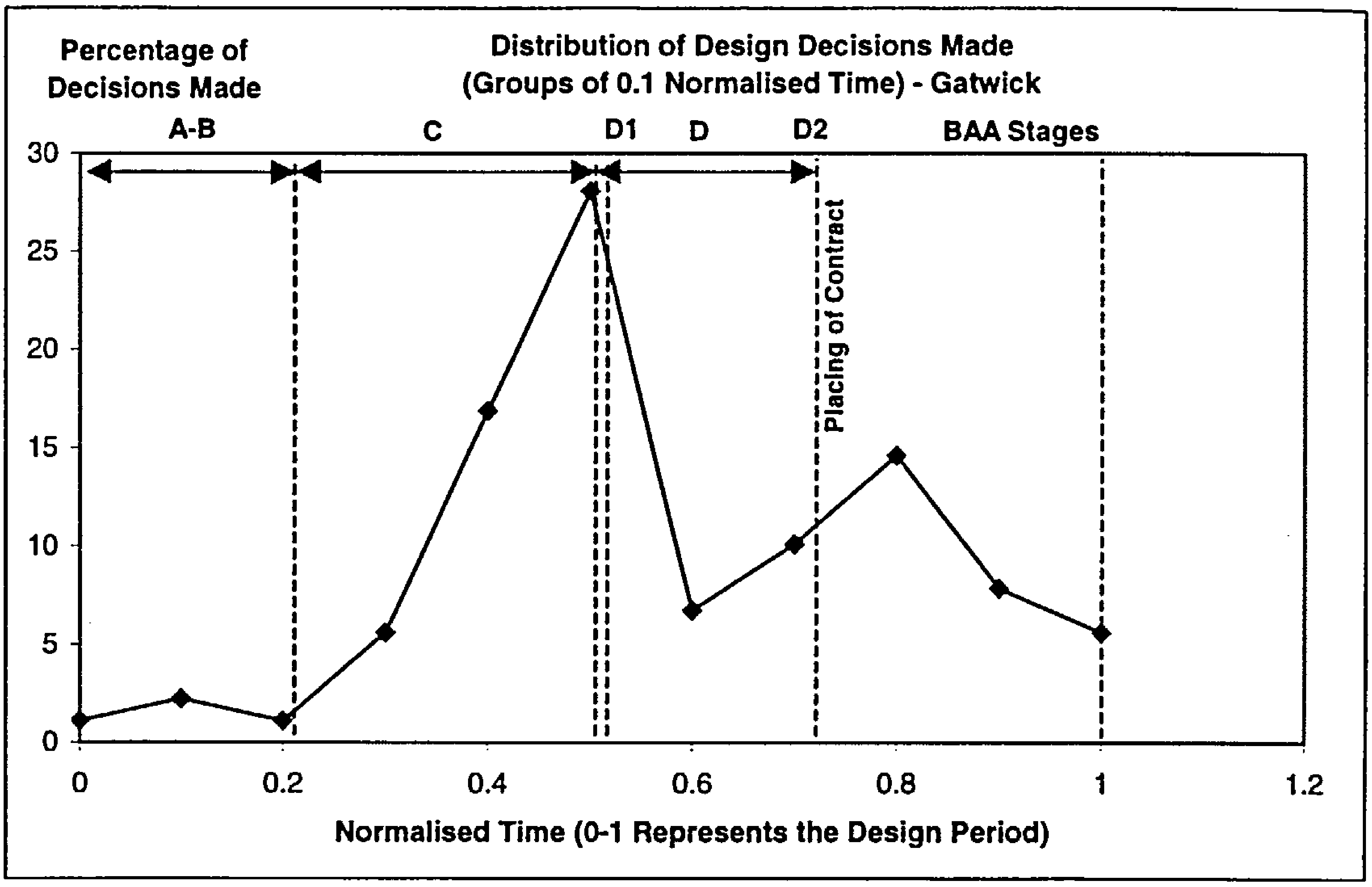


Figure 7.3 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) - Gatwick

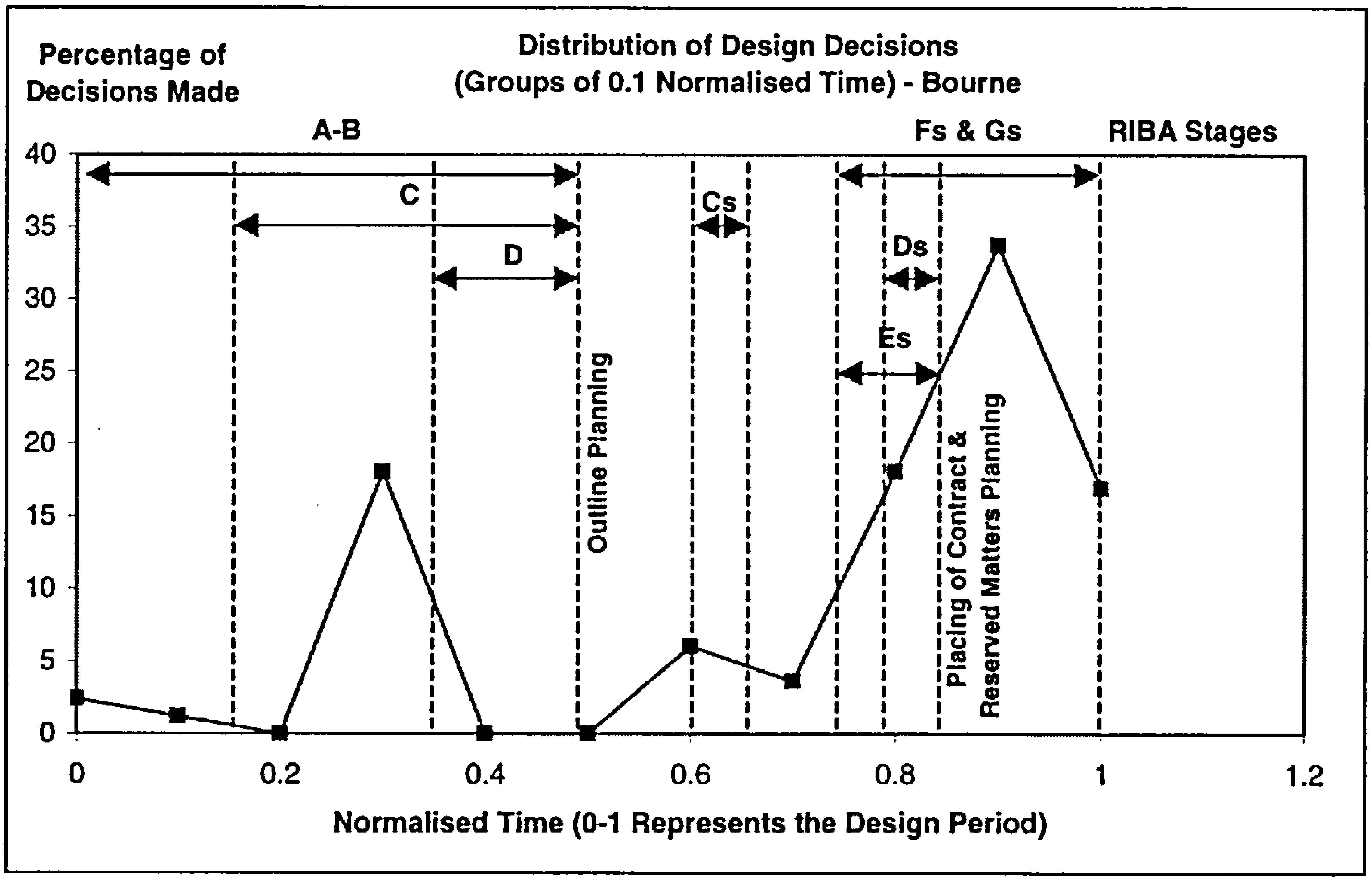


Figure 7.4 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) – Bourne

Although figures 7.2 – 7.4 only reflect one level of design decisions, namely system / sub-system, they have implications for the level of resource required over time. However, the graphs do not reflect efforts required for briefing in the early stages, nor the efforts for detailing in the later stages. This could be the subject of further study and combined with the current data.

Figures 7.5 – 7.7 show matched decisions between each pair of case studies plotted along a normalised time axis. Figure 7.5 shows the Gatwick and Chelmsford case studies. The decision codes are made up of two numbers, 86-50, for example. This represents Gatwick decision number 86 and its equivalent number 50 for Chelmsford. The numbers are not the order in which decisions were made but rather the database number that was assigned to each decision for data processing purposes. Where a code has two numbers two dots will be plotted, one for each case study. The dots indicate the time when that particular decision was taken within the scope of each project. Where a code includes a '0' this means that there was no equivalent decision for the particular case study. Consequently, only one dot will be plotted. The ordering of the case studies, and therefore code parts, is indicated on each figure. For a list of decisions made in each case study refer to appendices G, H and I. Table one in each appendix provides a list of decisions listed in the order in which they were made. For a list of decisions ordered by database number, view the table showing a 'List of System / Sub-System Level Design Decisions with Corresponding 'Constraint' and 'Reasons For Selection' Categories Cited' – tables G.16, H.14 and I.19.

Normalised time is plotted along the y-axis. Where error bars are included they define a tolerance of ± 0.05 normalised time.

For each of the graphs the data was 'sorted' by *the date that the decision was made* in ascending order, first for one case study and then the second. This means that for one of the data sets (indicated on each graph) the plot forms a curve that seeks to follow a substantially diagonal path, from bottom left to top right. The other data set appears to be randomised about it. This means that the decisions taken in each project were made in different orders, and given that a large percentage of the dots lie outside the error bars, also at different points in time. So, although there is a large degree of commonality across projects, the timing and ordering of decisions is seen to be variable.

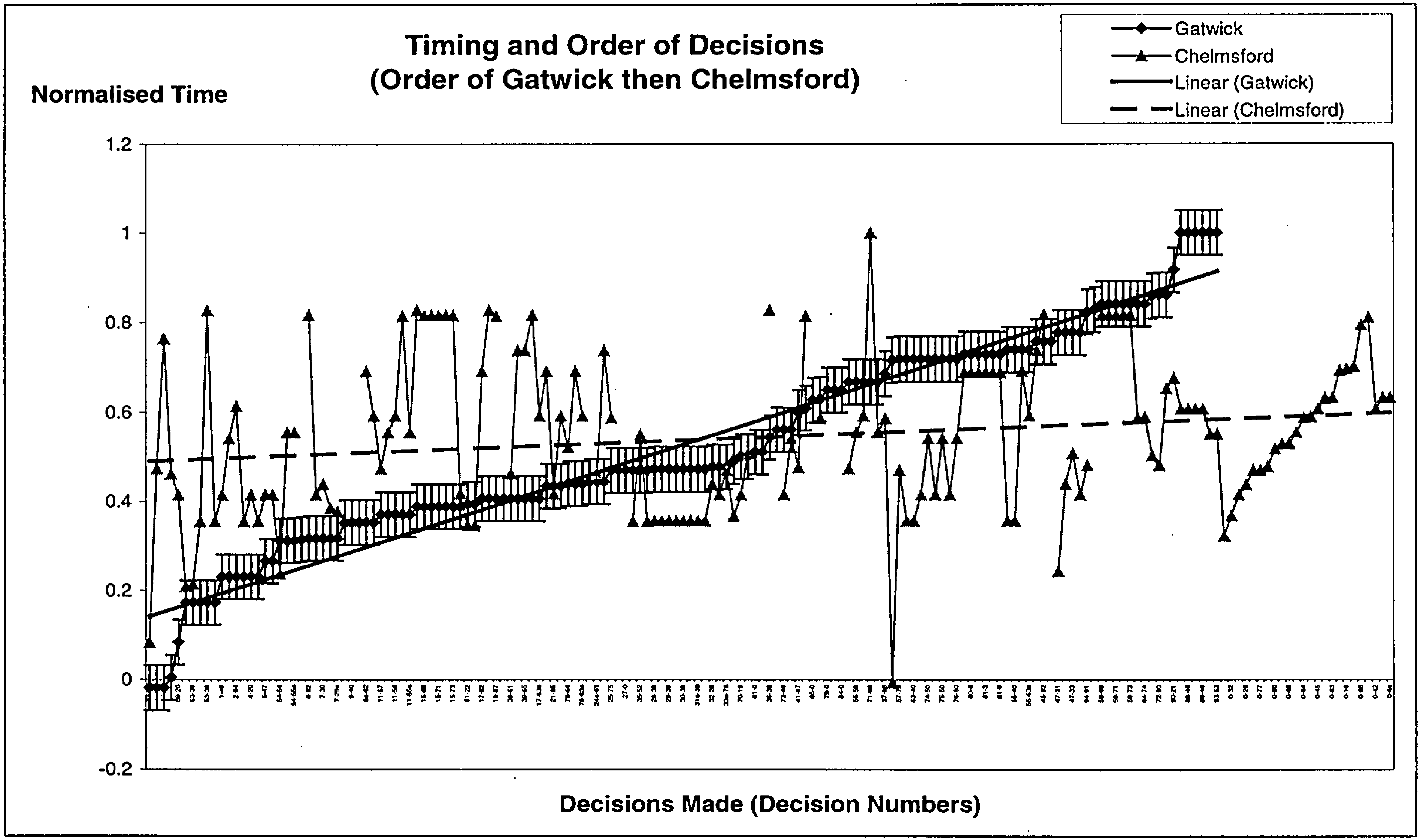


Figure 7.5 – Gatwick & Chelmsford Design Decisions Made Against Normalised Time

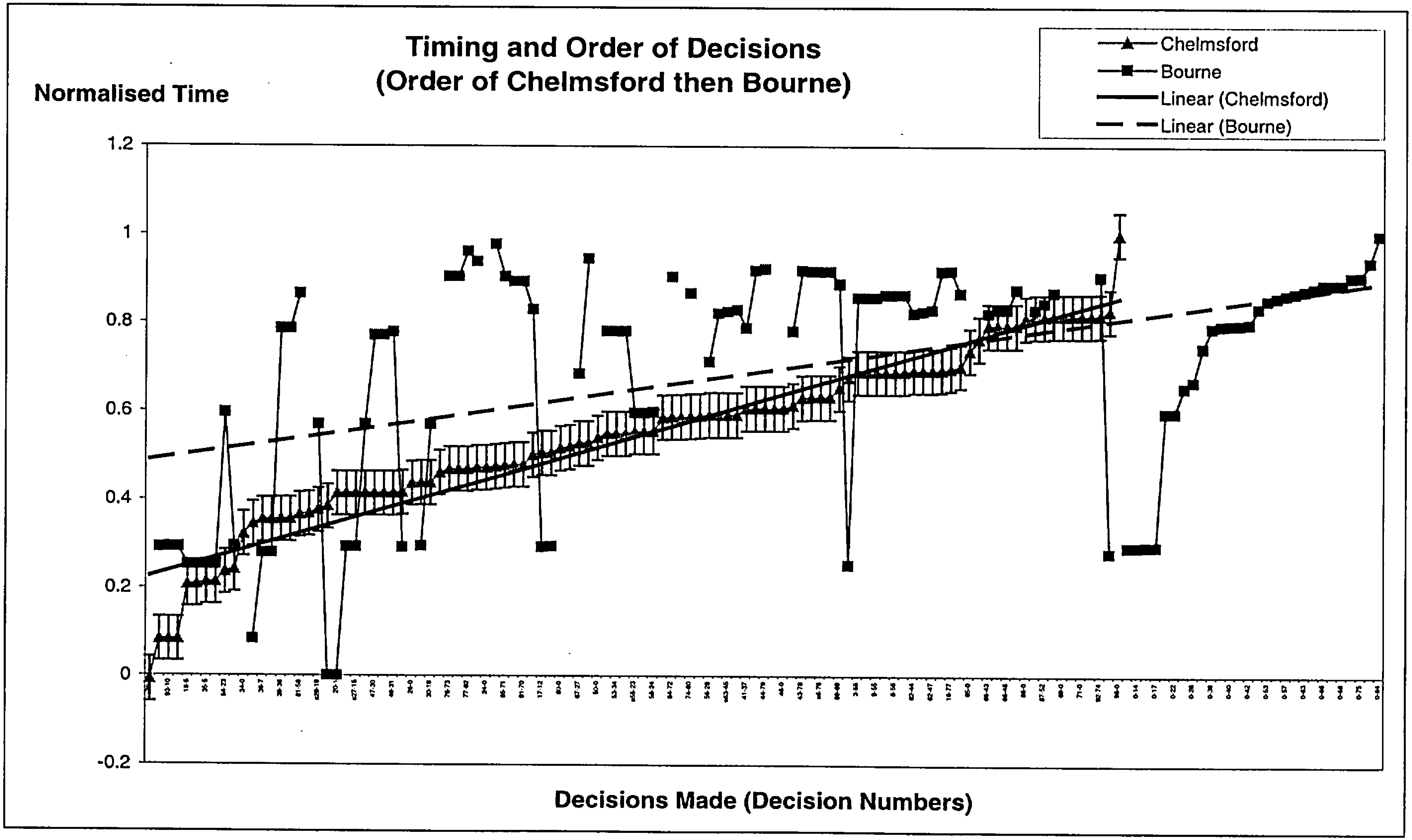


Figure 7.6 – Chelmsford & Bourne Design Decisions Made Against Normalised Time

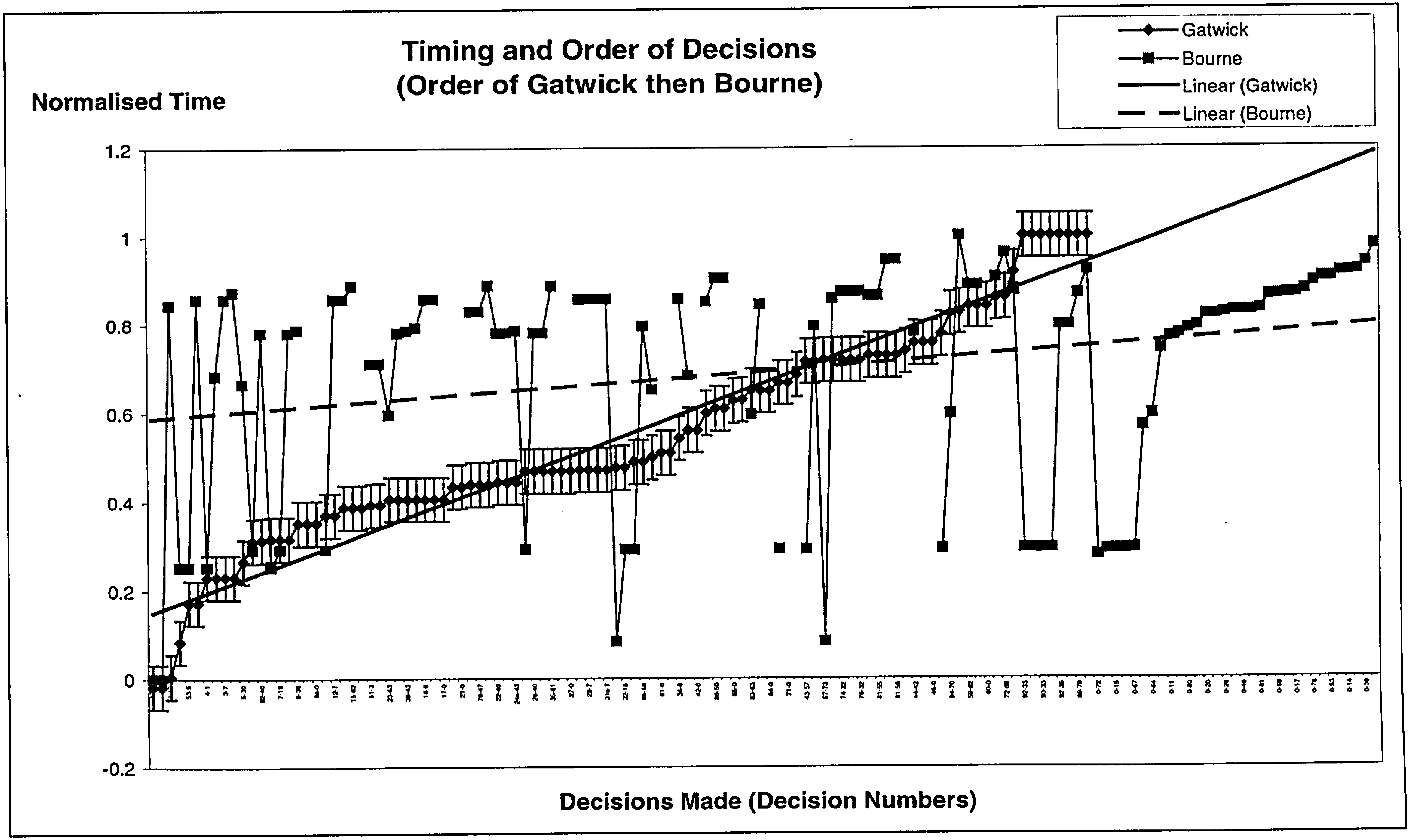


Figure 7.7 – Gatwick & Bourne Design Decisions Made Against Normalised Time

7.7 DEFINING THE DISCIPLINES

The data collected from the case studies also provides insights into the role of each discipline throughout the decision making process. Figures 7.8 – 7.10 show the percentage of the system / sub-system level design decisions made by each discipline. These figures can be read in conjunction with tables G.4, H.3 and I.4 in appendices G, H and I. The tables show the actual decisions which were made by each of the disciplines.

A decision was defined as being made by a particular person when they had the final say for a particular course of action. This was very rarely performed in complete isolation from other design team members. Often discussions with other disciplines would take place over a period of days, weeks or even months before a decision was finally made. Figures 7.11 – 7.13 show the percentage of design decisions in which the design team members played an active role, but did not necessarily make the final decision. This provides an indication as to how each discipline actively supported the entire design decision making process. These figures can be read in conjunction with tables G.5 – G.15, H.4 – H.13 and I.5 – I.18 in appendices G, H and I. These tables show the decisions that each discipline played an active part in making, but were not necessarily made by that person.

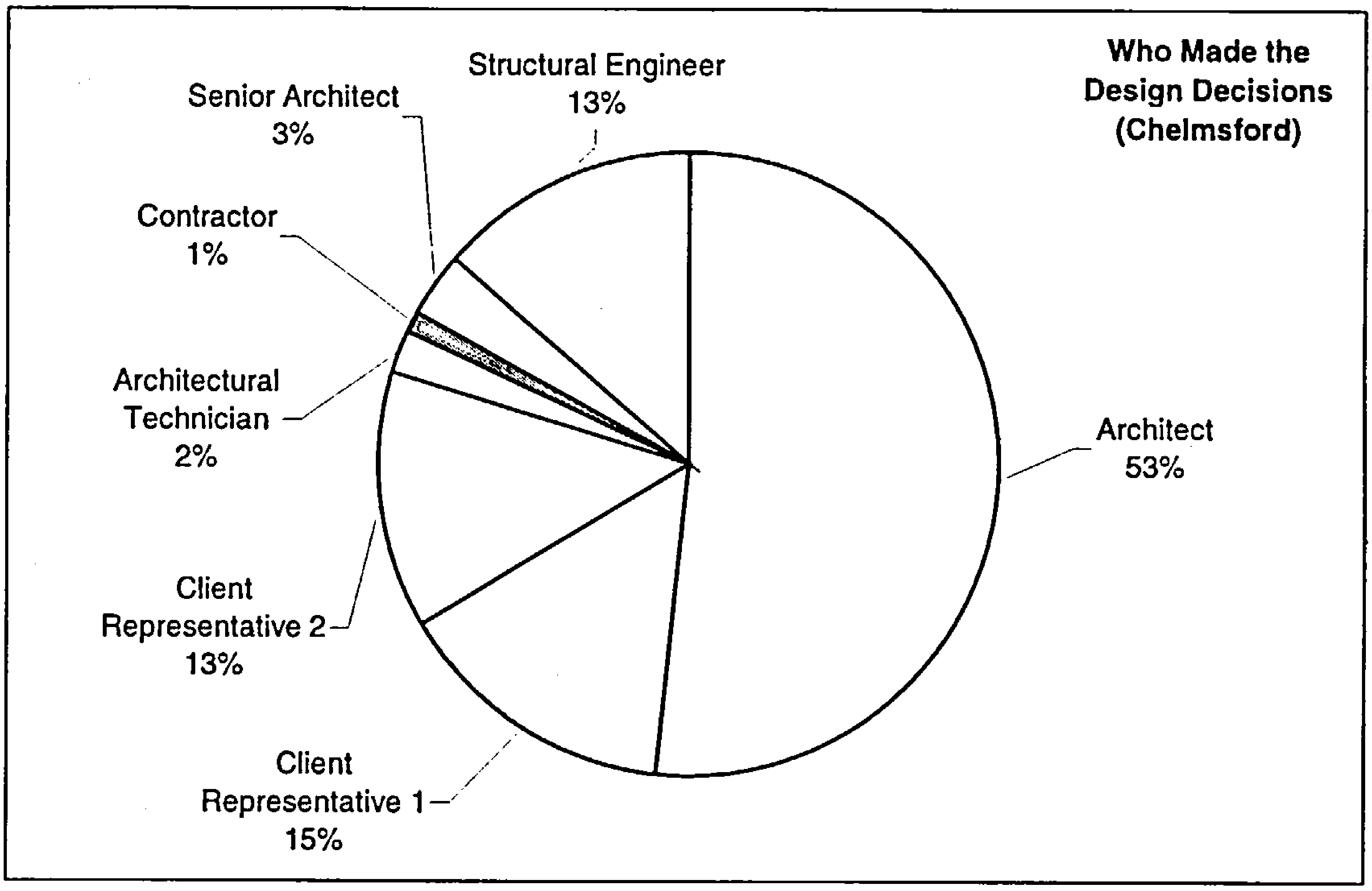


Figure 7.8 – Who Made the Design Decisions (Chelmsford)

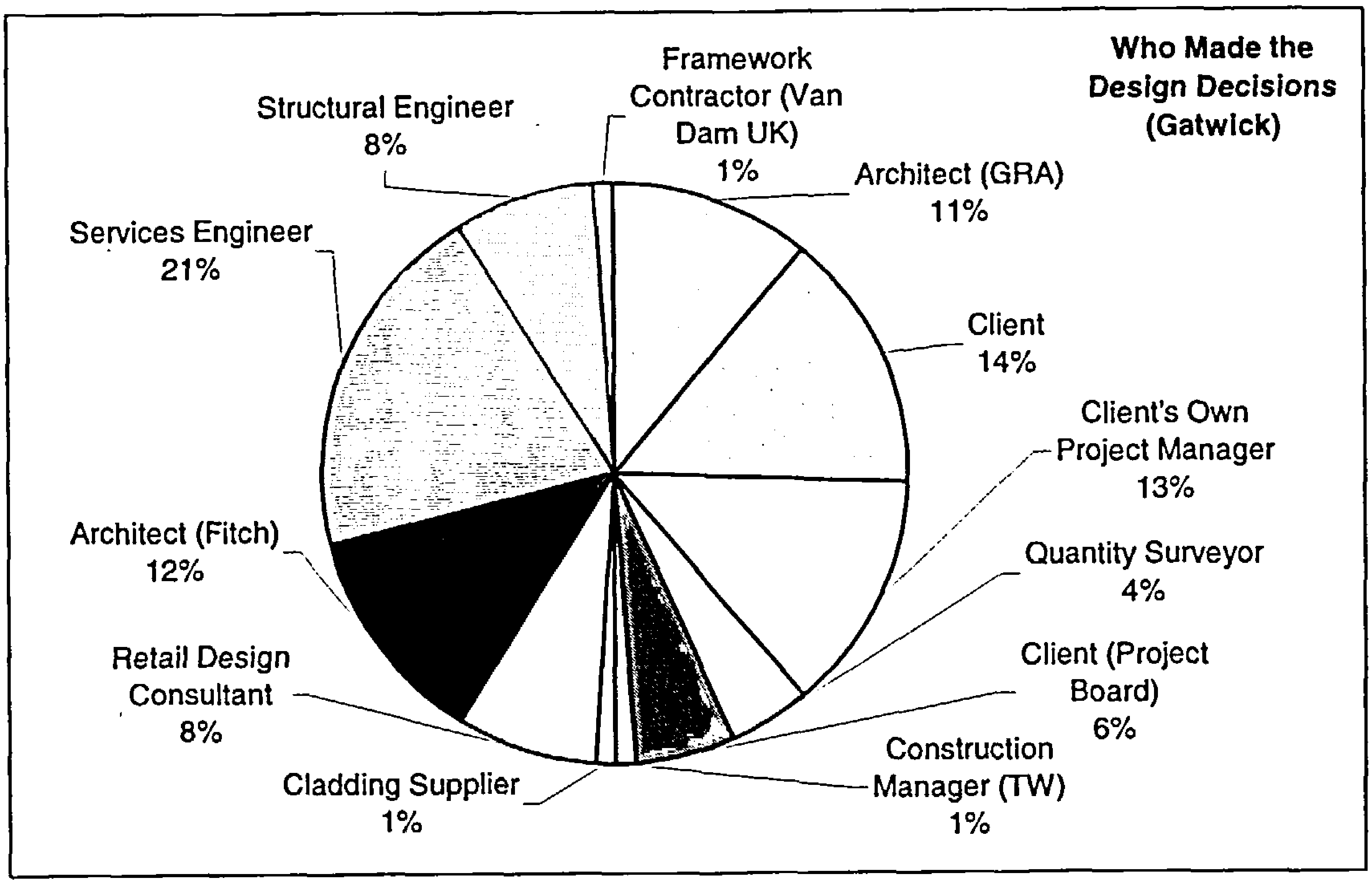


Figure 7.9 – Who Made the Design Decisions (Gatwick)

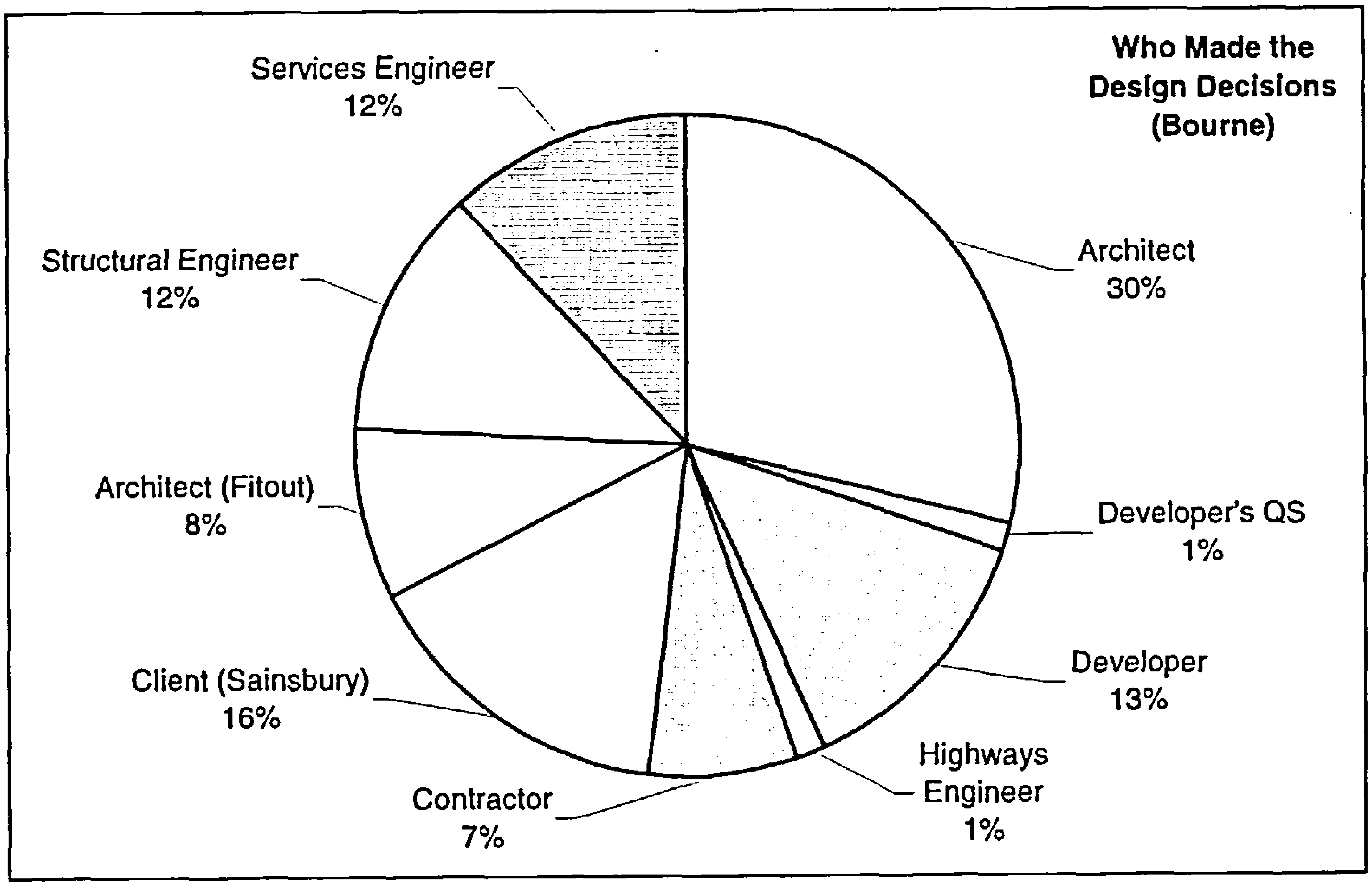


Figure 7.10 – Who Made the Design Decisions (Bourne)

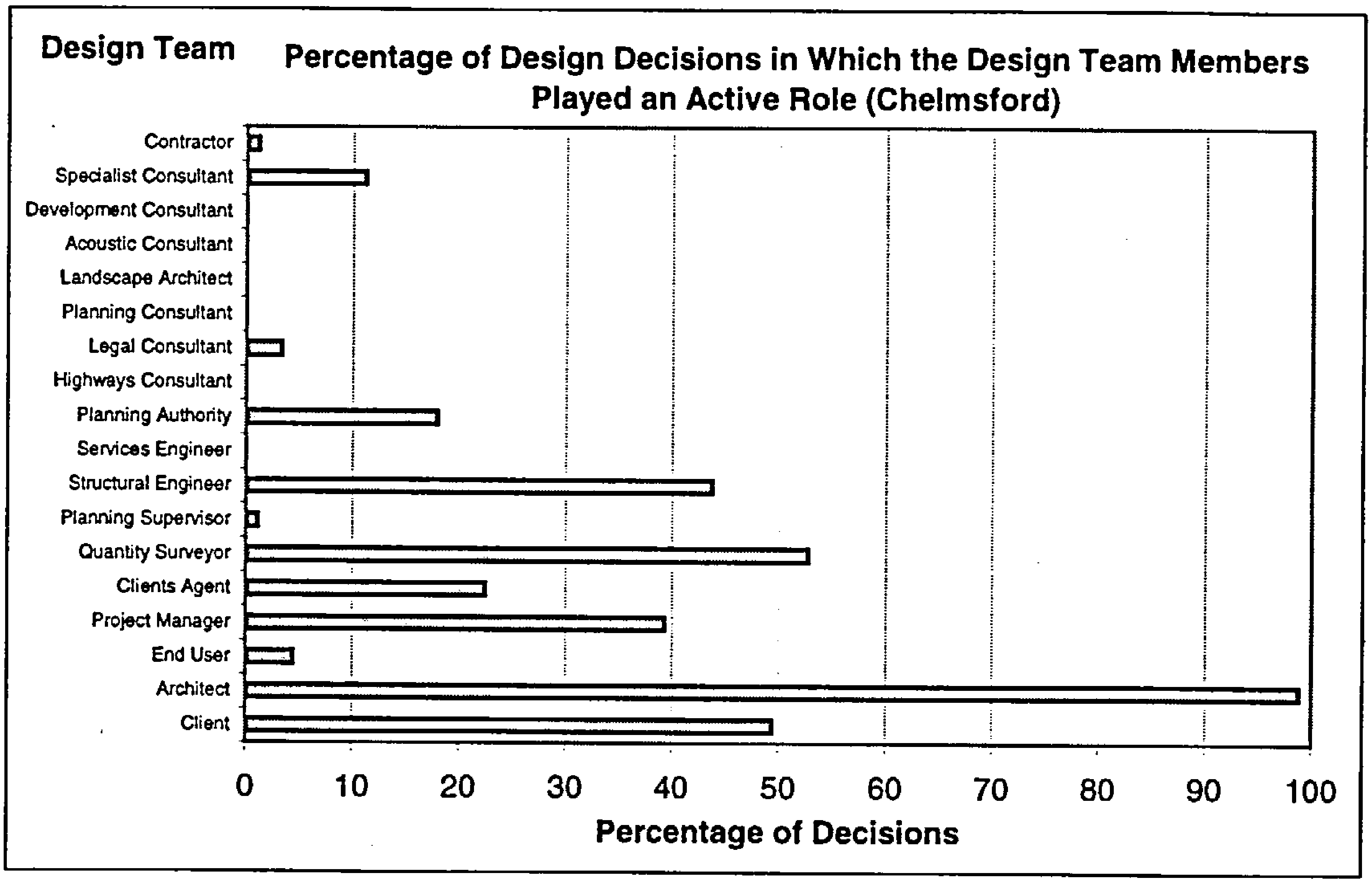


Figure 7.11 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Chelmsford)

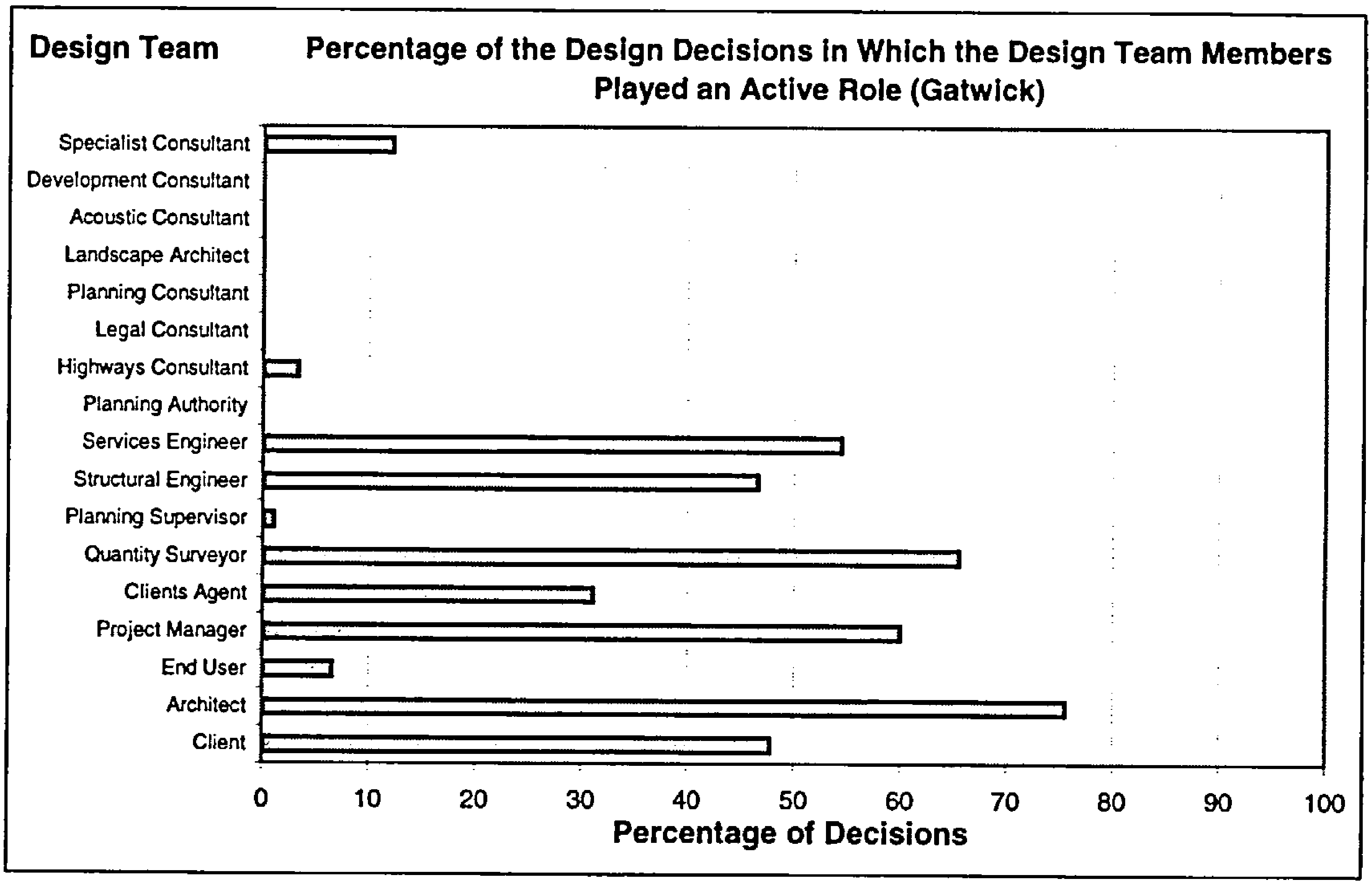


Figure 7.12 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Gatwick)

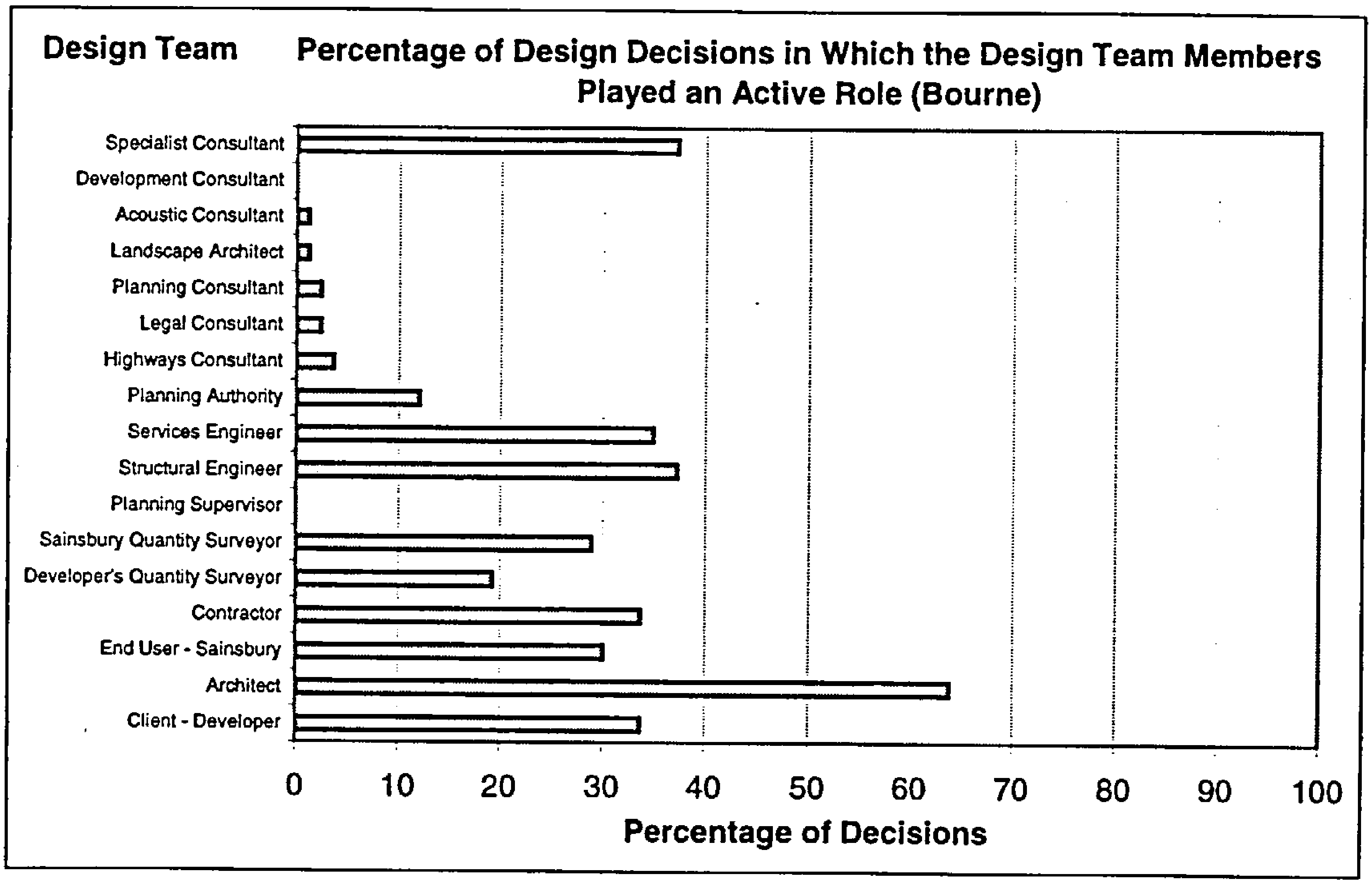


Figure 7.13 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Bourne)

In the Chelmsford case study (figure 7.8) the architect makes 53% of the system / sub-system level design decisions and the client body 28%. This means that more than 80% of the design was decided upon by two disciplines. For Gatwick the situation is quite different (figure 7.9). Decision making is much more evenly spread throughout the project team. The client body made 33% of the decisions through three different representations (client's representative, project board and client's project manager). The total architectural input was 23% through two architectural practices with the services engineer and structural engineer making 21% and 8% of the design decisions, respectively. Interestingly, although suppliers are available for consultation and do indeed contribute at this decision level, the actual number of decisions that they made is a small fraction of the total number ~ 3%. In the Bourne case study there is a large degree of dependency upon the architectural discipline with a total of 38% of the design decisions made between two architectural practices (figure 7.10). Both of the engineering disciplines make 12% of the decisions with the developer and end user client making 13% and 16% respectively. The contractor also makes a number of decisions in the Bourne case study, as the design and build procurement route was taken. Interestingly, in all three case studies the quantity surveyor makes few or no system / sub-system level design decisions. Viewing figures 7.11 – 7.13, it can be seen that the quantity surveyor is actively involved in a significant proportion of the decisions made, but does not actually take responsibility for making the decisions. The same graphs show that the architect is the most active discipline at this level of design. It can also be seen that the members of the Gatwick team are more actively involved in a larger number of design decisions, on average, than the Chelmsford and Bourne teams. This may be due to the BAA framework agreement indicating from an early design stage who is to be involved in the project and the client's desire to improve the construction design process to effect greater value for money, and fulfil the Egan targets. Also, in all three projects the clients collaborate closely with the design team. This is likely to be due to the clients' level of sophistication and experience (see table 7.4).

All of the decisions which are made by each discipline are likely to be heavily influenced by the contractual arrangements for each project as the contract defines the disciplines' responsibilities.

7.8 WITHIN THE LIMITS: CONSTRAINTS & SELECTING DESIGN OPTIONS

One of the most crucial aspects to successful design is the identification and exploration of constraints. Constraints are essentially design boundaries that the designer has to work within. Constraints can be physical such as the tensile strength of a material or softer issues such as a desired look or quality. Often in the construction environment the client is a source of a number of constraints such as budget, programme and functional requirements. If a solution is generated that falls outside these boundaries then it should be rejected, else suffer the consequences. In some instances the consequences may be fairly minor, in others it might cost the project considerable sums of money or even termination of the project, with litigation to follow.

For each of the decisions recorded on each live project a number of design constraints were also documented. These constraints were arranged into categories which can be seen in table 7.11. Figures 7.14 – 7.16 show the percentage of design decisions that particular constraint categories are cited as impinging upon the design process, for each case study. With regard to the data processing, if more than one constraint of the same type was documented for a particular decision, 'physical constraint' for example, it was only entered once for the purposes of generating figures 7.14 – 7.16 as they show the percentage of decisions that had at least one constraint of each category, or 'type' of constraint. This is also true of tables G.16, H.14 and I.19 in appendices G, H and I which show each design decision and the constraint categories cited.

Table 7.12 shows the five most common constraint categories documented for each design decision. There is a large degree of commonality between the projects with D – 'physical constraints', F – 'interfacing issues' and L – 'building regulations / planning authority influence / standards' appearing in the top five for each case study. Also included in the top five for both Chelmsford and Bourne is K – 'functional issues / fitness for purpose'. Constraint category I – 'economic issues' is represented in both Chelmsford and Gatwick with M – 'client requirements / preferences and B - 'end user requirements / preferences' being important for Gatwick and Bourne, respectively. In the Bourne case study constraint category C – 'design guides' is the sixth most common. This is because the end user, JS Sainsbury, relies heavily on 'in house' design guides when procuring new buildings. Unsurprisingly, the most common constraints relate to physical and functional issues, economic and client / end user preferences. What is surprising is that constraint category O – 'time issues', i.e. programme, is not prominent in any of the three projects, yet all three projects were considered to be on a tight time schedule. This suggests that, although there is a pressure to perform work quickly and meet pressing deadlines, it is not clear to designers how this impacts individual design decisions. Another constraint which was seldom cited is V – 'quality'. This could be because quality is a somewhat nebulous characteristic which is poorly defined and therefore not well understood, or that clients are more interested in time / cost issues than quality. From a cynical perspective the latter argument might hold for buildings procured by developers but is less likely to be true of projects with owner-occupiers.

Constraint Code	Category Description
A	Flexibility
B	End user requirements / preferences
C	Design guides
D	Physical constraints
E	Efficiency / Optimisation
F	Interfacing issues
G	Least disruption on organisation's operations
H	Buildability
I	Economic issues
J	Strategic approach to design
K	Functional issues / Fitness for purpose
L	Building regulations / Planning authority influence / Standards
M	Client's requirements / preferences
N	Health & Safety
O	Time issues
P	Maintenance
Q	Aesthetic
R	Archaeological
S	External stakeholders
T	Contractual / Legal
U	Market issues
V	Quality
X	Access (other than Maintenance) & People / Material / Information flows
Y	Lacking information
Z	Security issues

Table 7.11 – Constraint Category Codes and Descriptions

	Chelmsford	Gatwick	Bourne
Five Most Important Constraint Categories Cited	D, F, L, K, I	F, D, I, M, L	D, B, K, F, L

Table 7.12 – Five Most Common Constraint Categories Cited for each Case Study

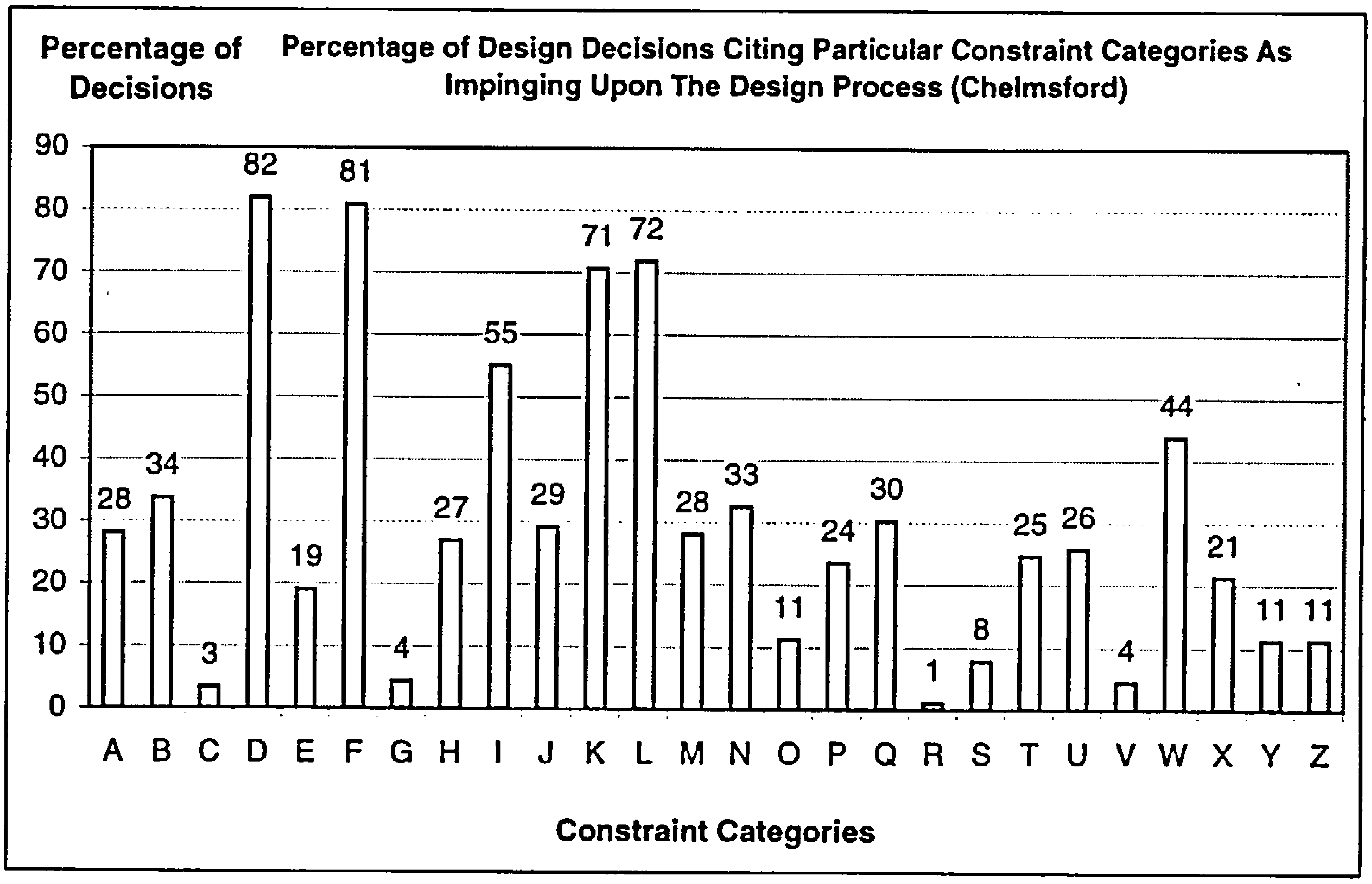


Figure 7.14 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Chelmsford)

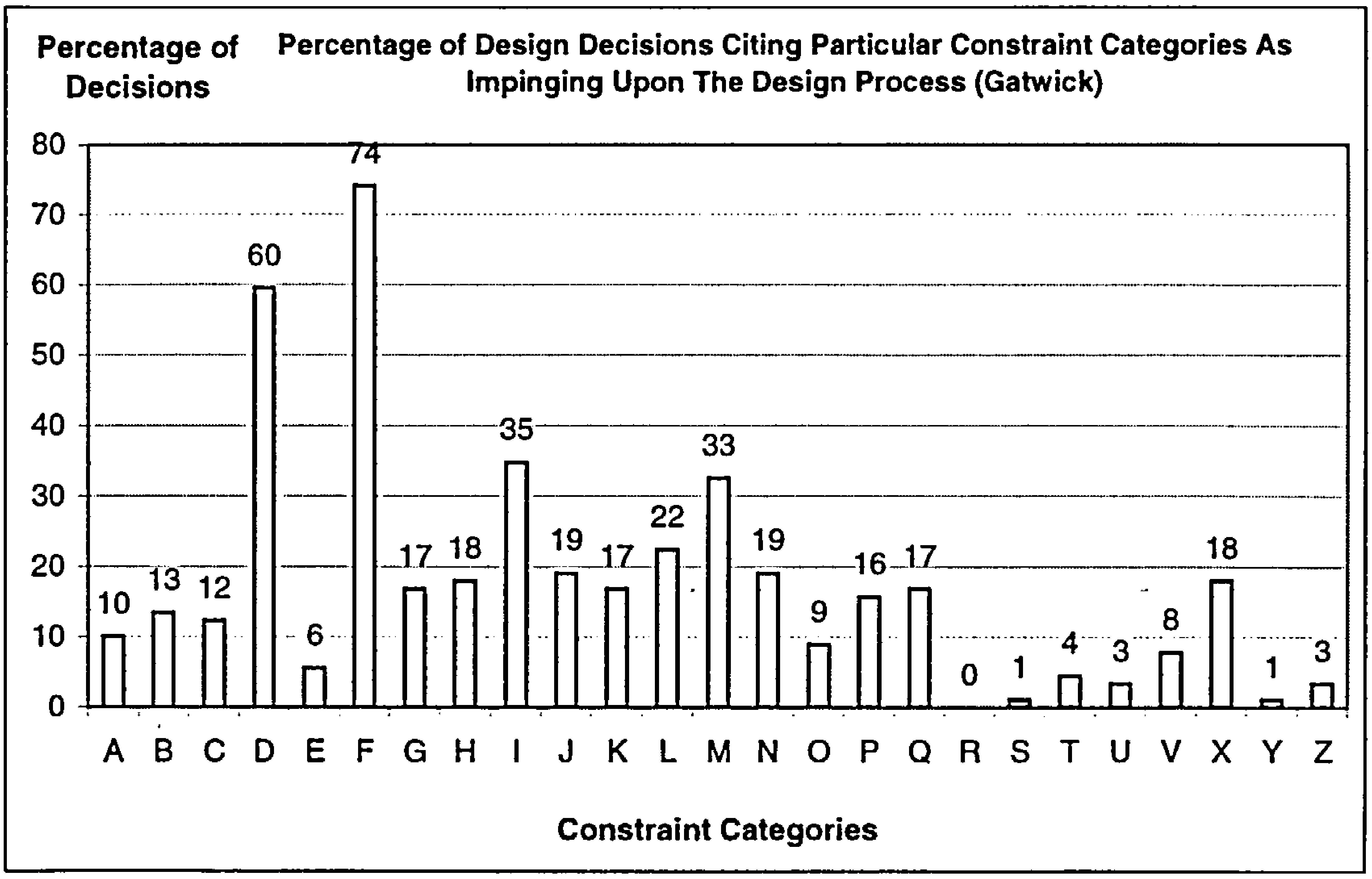


Figure 7.15 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Gatwick)

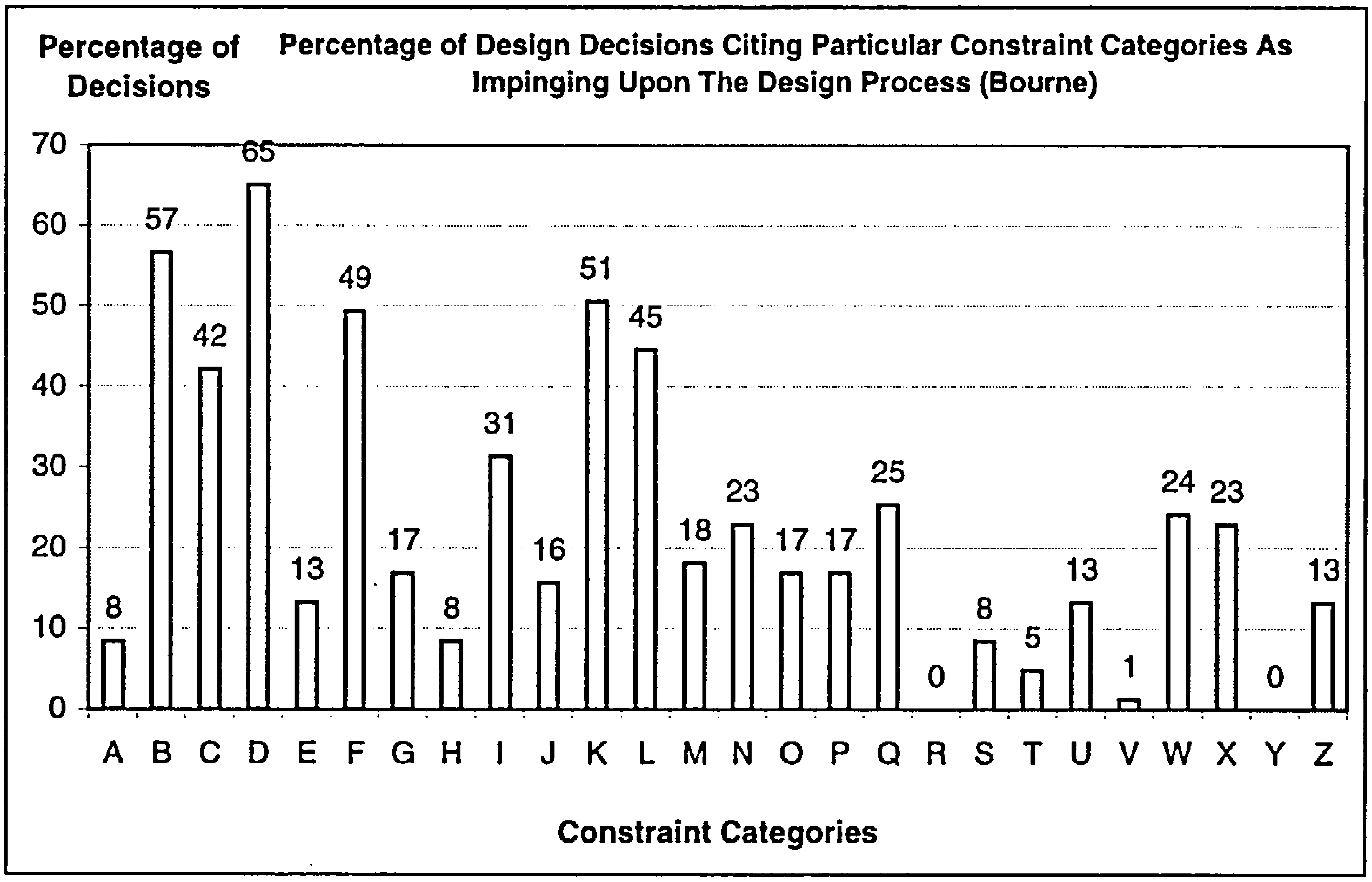


Figure 7.16 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Bourne)

Having established the boundaries for design and having generated a number of viable options, the designer then has to make a decision as to which option is the best within the identified constraints. When each design decision was recorded the reasons why a particular option was selected, and the others rejected, were also documented. In a similar fashion to the design constraints, these reasons were categorised. Table 7.13 shows the reason category codes and their descriptions.

Figures 7.17 – 7.19 show the percentage of design decisions using particular reason categories to choose between options for each of the three case studies. These can be read in conjunction with tables G.16, H.14 and I.19 in appendices G, H and I which show each design decision and the reason categories cited.

Reason for Selecting Option Code	Category Description
A	Most obvious choice
B	Experience / Professional judgement
C	Design guides
D	Designing to account for worst case scenario
E	Only feasible option
F	Interfacing issues
G	Least disruption on organisation's operations
H	Buildability
I	Economic issues
J	Utilise standard components / approaches
K	Functional issues / Fitness for purpose
L	Building regulations / Planning authority influence / Standards
M	Client's requirements / preferences
N	Health & Safety
O	Time issues
P	Maintenance
Q	Aesthetic driver
R	Archaeological issues
S	External stakeholders
T	Market issues
U	Flexibility
V	Security
W	Legal / Contractual

Table 7.13 – Reason for Selecting Design Options Category Codes and Descriptions

Table 7.14 shows the five most common reason categories for choosing between options for each case study. All three case studies include reason categories F – 'interfacing issues', I – 'economic issues' and K – 'functional issues / fitness for purpose'. Chelmsford and Gatwick have H – 'buildability' and Gatwick and Bourne have M – 'client's requirements / preferences'. Chelmsford and Bourne also have L – 'building regulations / planning authority influence / standards' and J – 'utilise standard components / approaches', respectively.

	Chelmsford	Gatwick	Bourne
Five Most Important Reason Categories Cited	K, F, I, L, H	I, K, F, H, M	K, M, I, J, F

Table 7.14 – Five Most Common Reason Categories for Choosing Between Options Cited for each Case Study

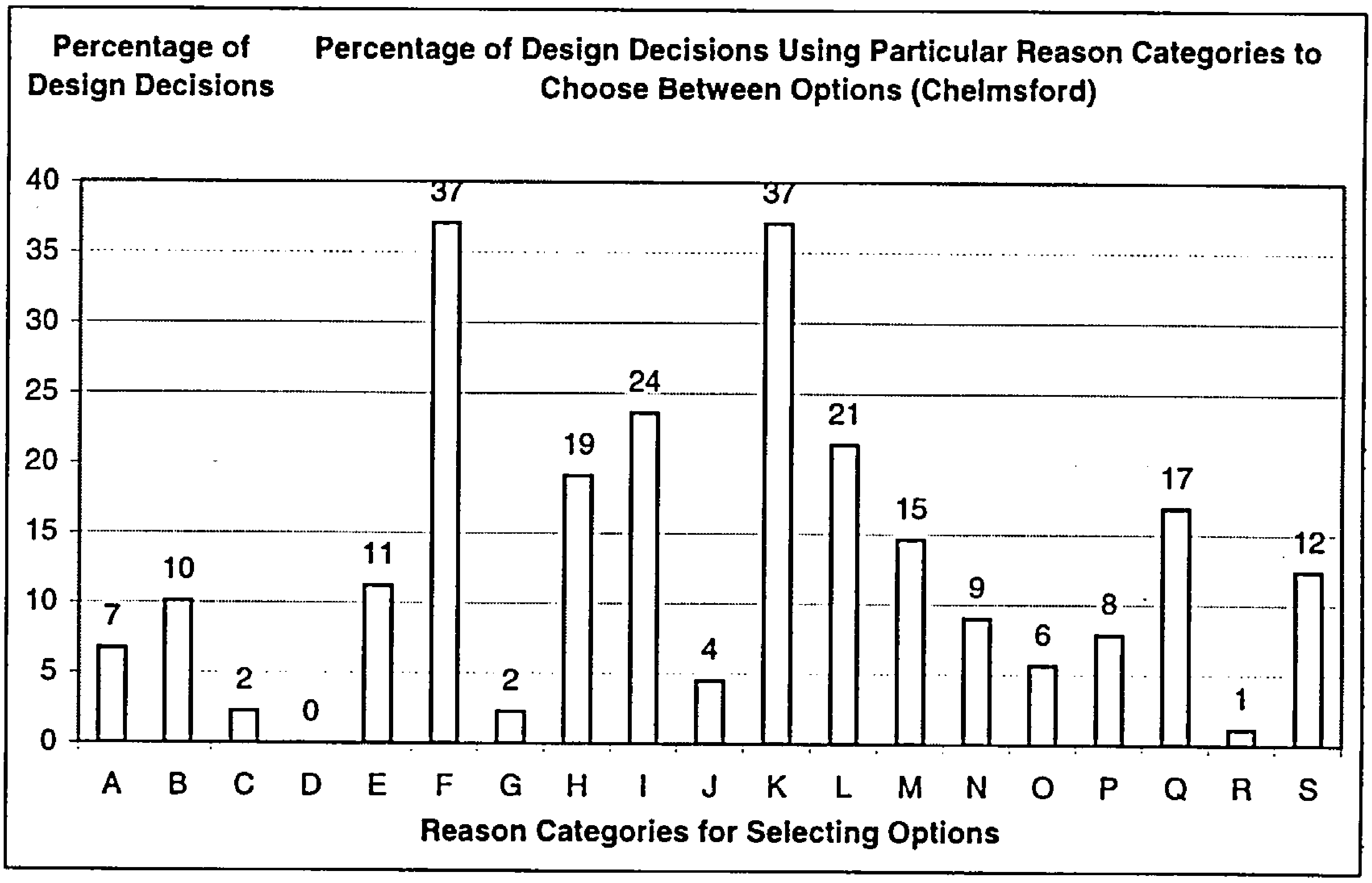


Figure 7.17 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Chelmsford)

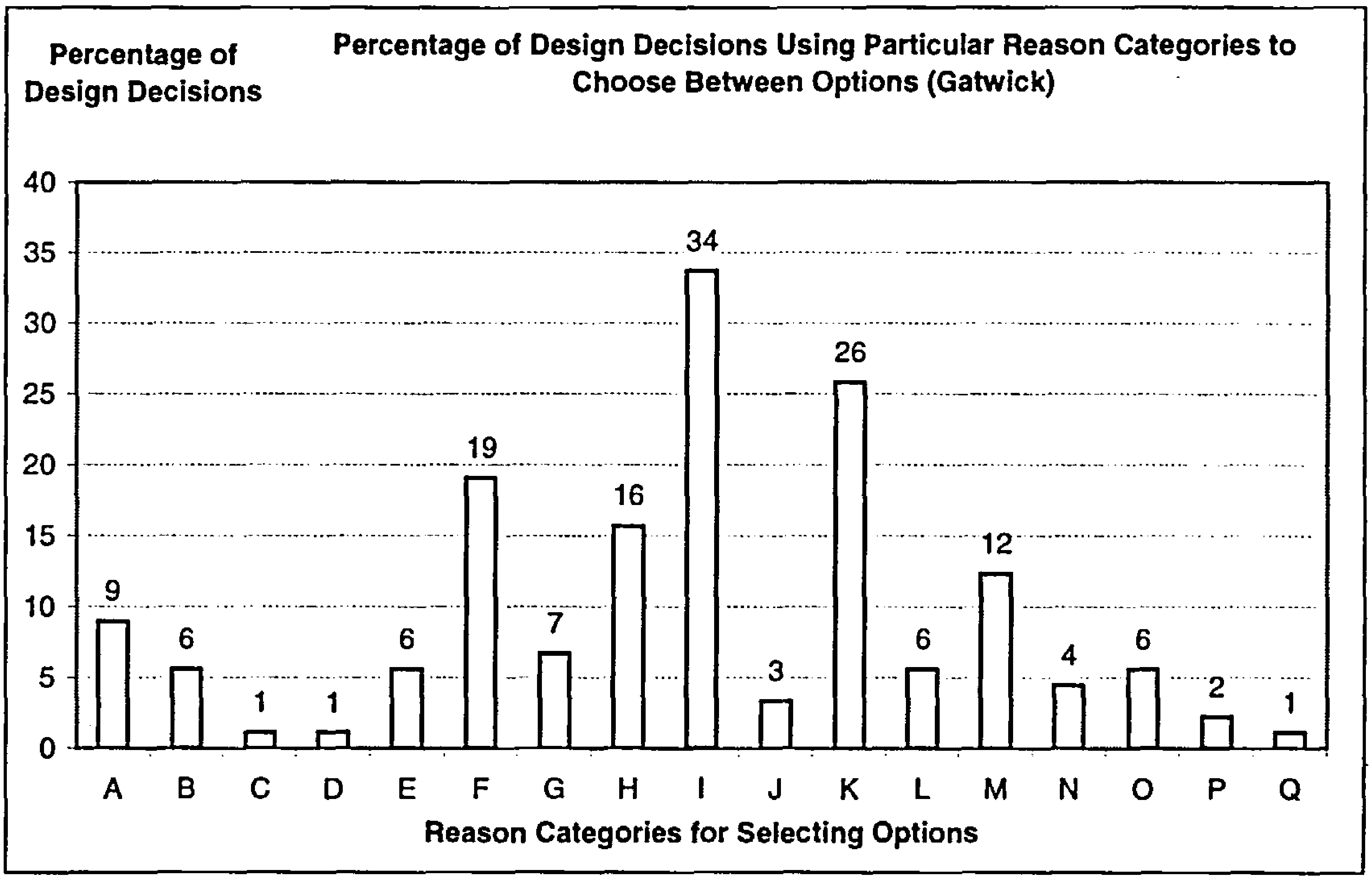


Figure 7.18 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Gatwick)

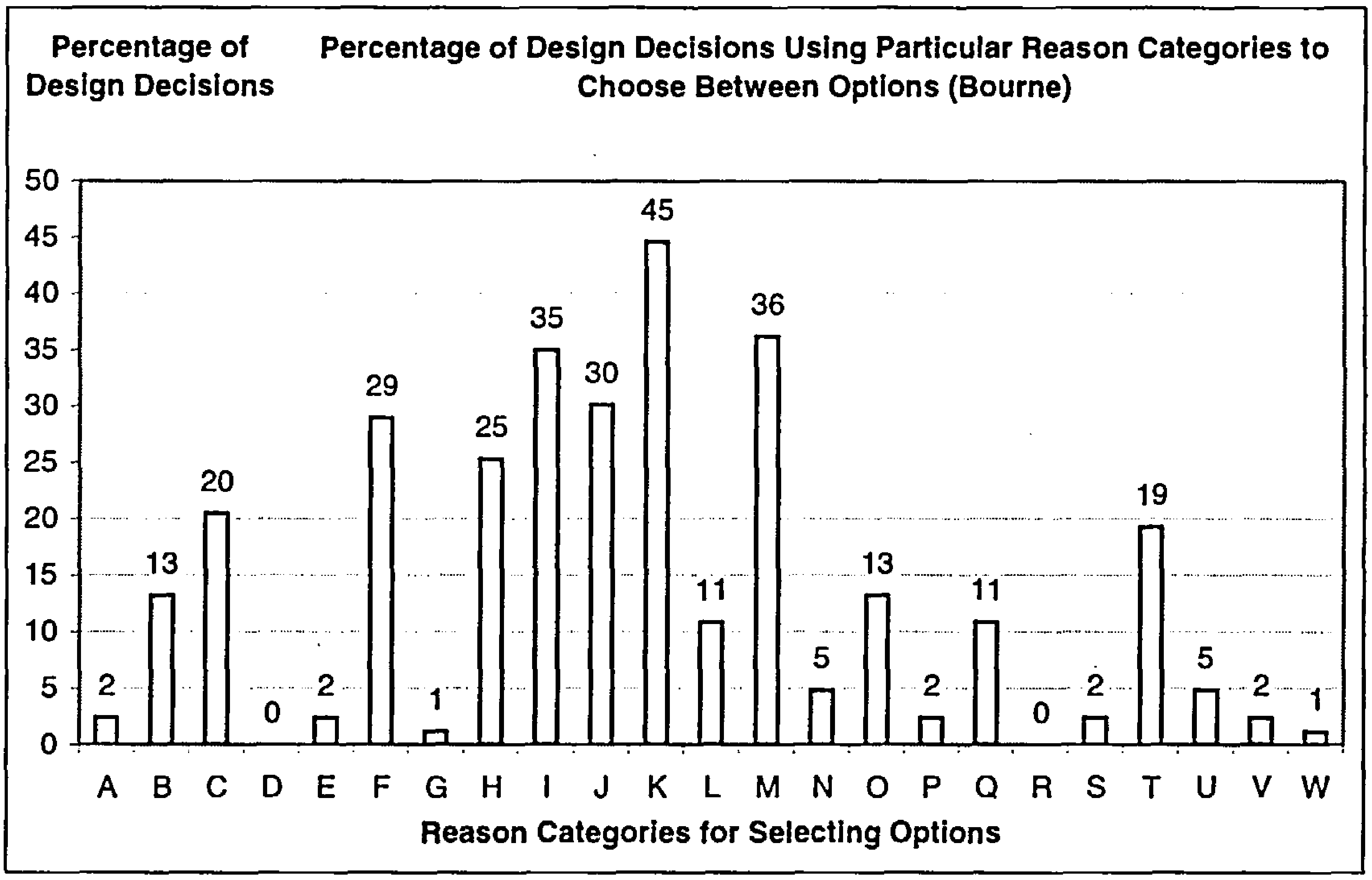


Figure 7.19 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Bourne)

Table 7.14 shows a high degree of commonality across the three case studies. Again, unsurprisingly, issues of function, interfacing and economics are the primary reason drivers when choosing between options. It is interesting to see 'buildability' and 'standard components / approaches' being of significant importance to designers, although it was not entirely clear from the study what efforts had been made to establish which was the most easy to build of the options. As no tools or techniques were specified by the data collectors it seems fair to assume that, in most cases, it was based on the pool of knowledge and experience within the design team and external consultants used. The fact that 'building regulations / planning authority influence / standards' was a primary reason driver suggests that designers are quite tightly constrained by external bodies. There is of course justification for external bodies to represent indirect stakeholder interests, the degree to which their influence should stretch is of course debatable. However, given its high ranking in the constraint categories, it might have been expected to have a higher impact on all three case studies in terms of reason drivers. Another interesting feature is that reason driver J – 'utilise standard components / approaches' was important to the Bourne project. Perhaps more interesting is that it was not important to Gatwick even though there was an explicit design policy of making use of standard components and approaches.

7.9 COST & PROGRAMME VISIBILITY

As part of the investigation of the design decision making process, this study attempts to establish both the cost and programme visibility that the designers had when making the decision. That is, what awareness and understanding did the design team have of the impact that their choice would have on both economic and time factors when making system / sub-system level design decisions. The data collected was in the form of numbers – a sum of money (£s Sterling) and number of weeks, for cost and programme respectively. These numbers were accompanied by footnotes providing additional insights, where appropriate.

Figures 7.20 – 7.22 show the cost visibility that each design team had over normalised time. The 'ideal' cost visibility is simply the cumulative count of design decisions for each project (shown as a percentage of the total number of decisions for that project), hence, the different 'ideal' shapes for each case study. This means that if the design team had cost visibility for every system / sub-system level design decision that was made, it would be identical in shape to the cumulative count curve for that particular project, the 'ideal'. When data was provided about cost visibility in the form of an amount of money and / or a footnote the incidence was noted and a cumulative count curve produced. This curve is the extent of the cost visibility of the design team for each project. This curve can then be compared to the 'ideal' curve to gain insights into the extent of the 'actual' cost visibility.

These graphs are at the same time very revealing, but also a little misleading. This is because the cost visibility data provided was quite poor and often inconsistent. The author allowed the designers some latitude as comments such as, "The cost data is available but I don't have access to it" [at the time of collecting data] were taken as incidences of cost visibility. In most incidences the amounts of money that were recorded came from cost plans that were either early assessments made before the decision was taken or later cost plans that were refined on the basis of having made the decision. In other words, for most of the numbers provided, at the time of making the decision, the designer did not have an understanding as to how that decision would impact the project financially. The quantity surveyor costs the decision after it was made and therefore acts as a cost controller rather than an active member of the design process. Because of the way the data has been interpreted, this means that the 'actual' cost visibility curves show an enhanced cost visibility. Therefore, any of the curves presented should be read with due caution. It is the author's option that figures 7.20 – 7.22 only reveal the lack of 'real' cost visibility during the system / sub-system level design decision making process.

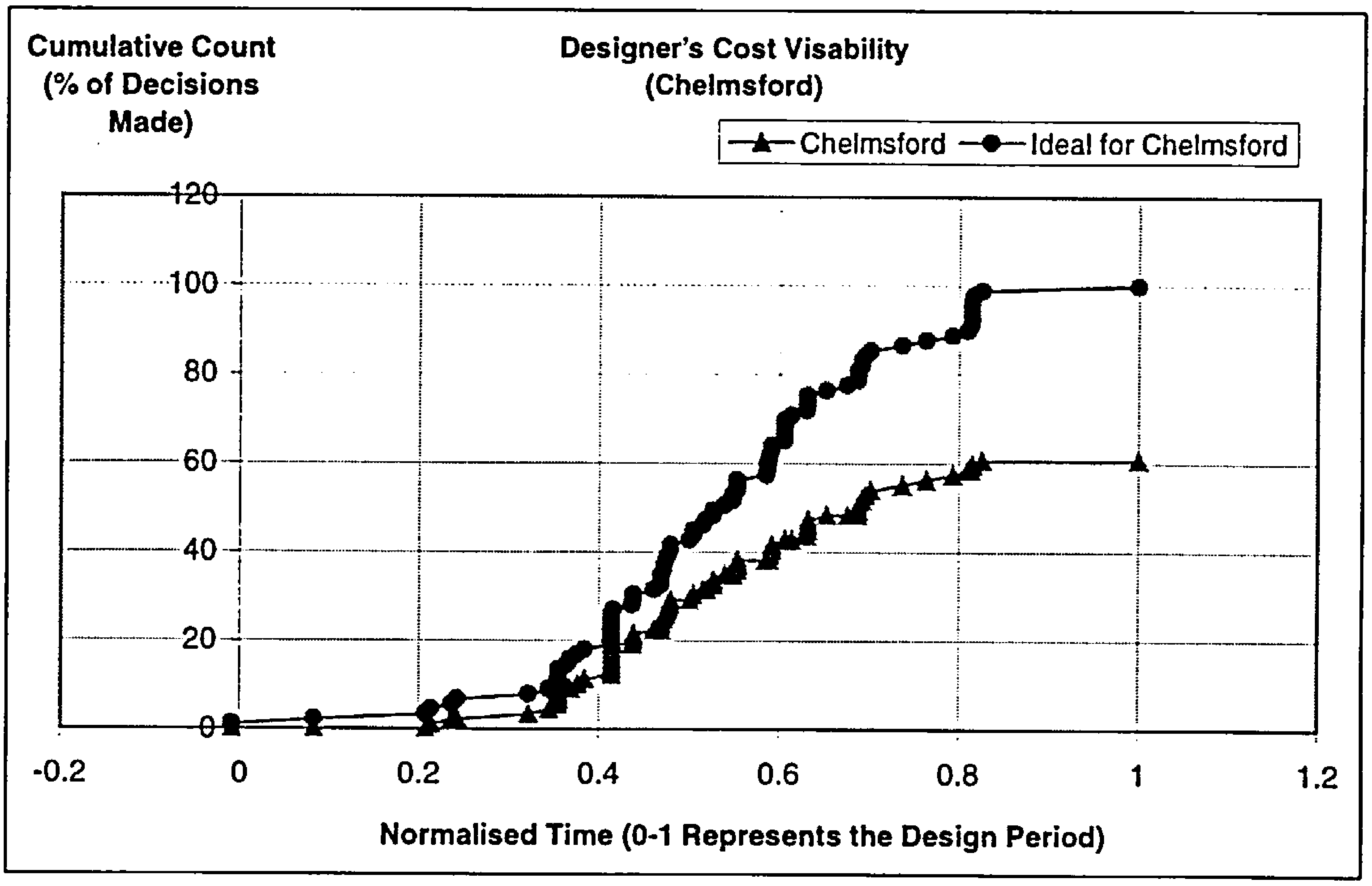


Figure 7.20 – Designer's Cost Visibility (Chelmsford)

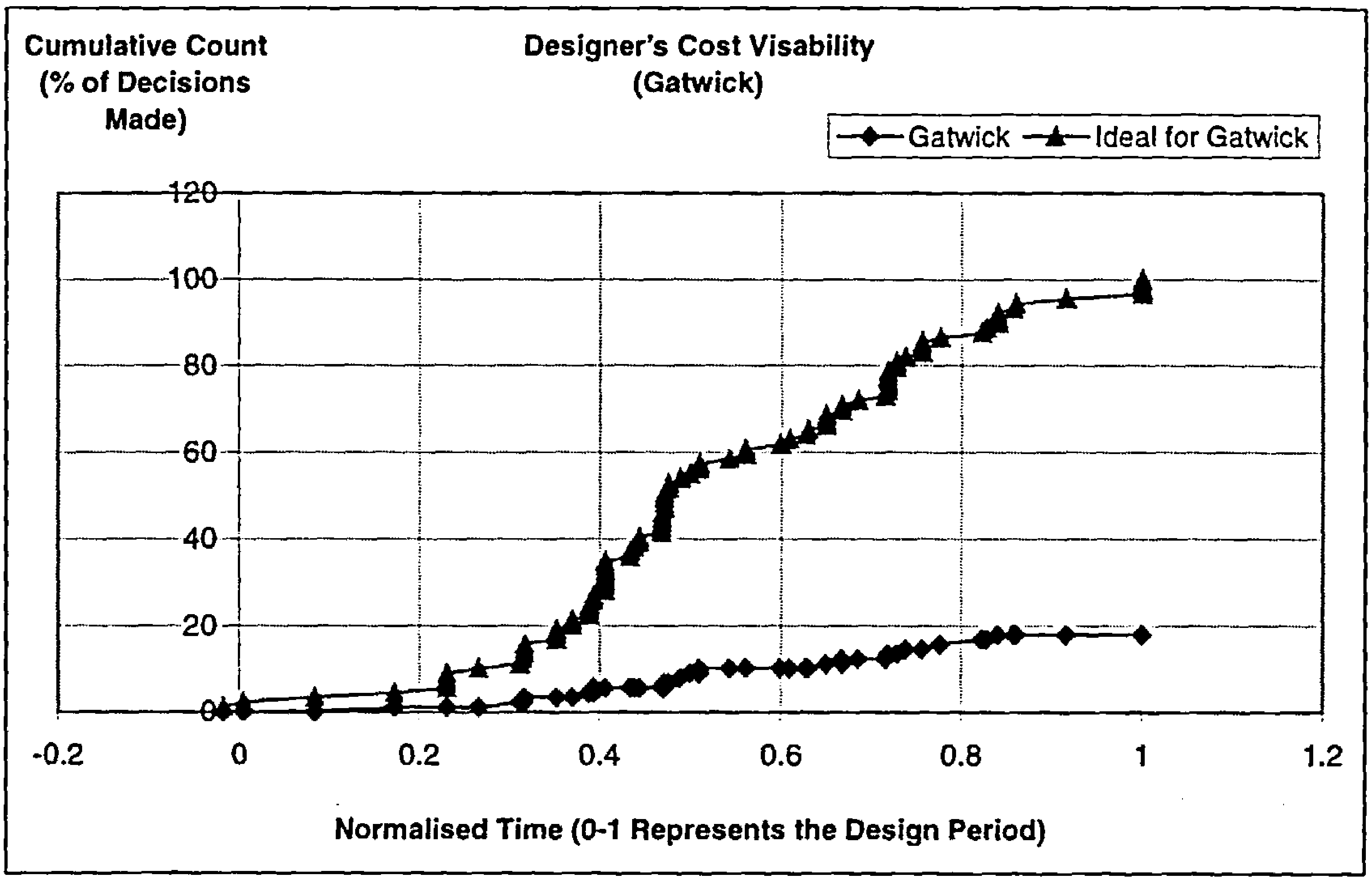


Figure 7.21 – Designer's Cost Visibility (Gatwick)

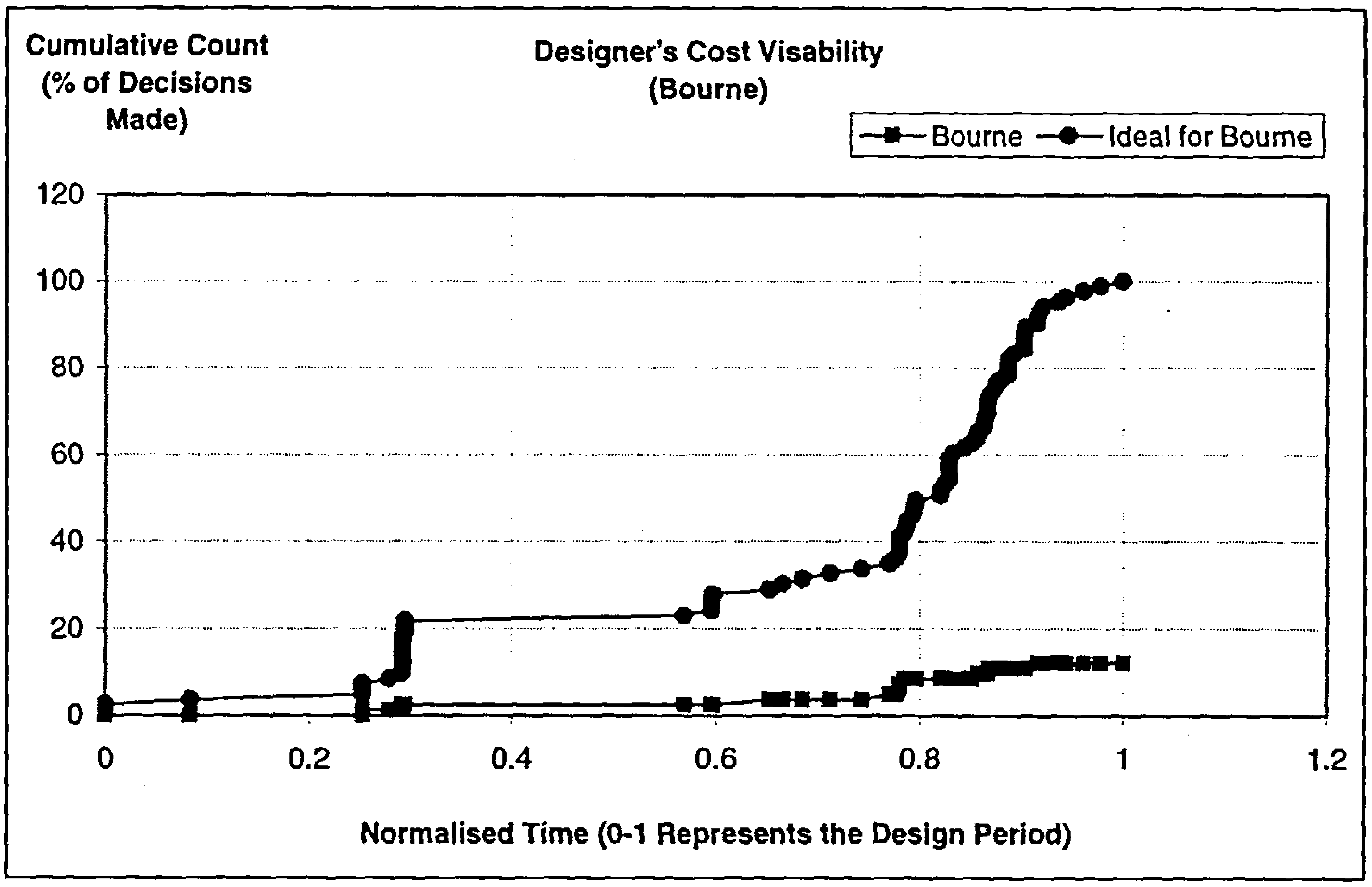


Figure 7.22 – Designer's Cost Visibility (Bourne)

In the case of programme visibility for system / sub-system level design decisions the information was so scarce that no graphs were produced. This means that the programme visibility is lower than the cost visibility. This is again very surprising given that these projects were time critical. There may be a programme component in the design team discussions when considering the suitability of particular options, such as, 'this system takes X weeks to install', or 'this system can be installed before that system because of this factor', however, visibility may be lower as in the majority of decisions this was not a crucial reason driver (see figures 7.17 – 7.19). Cost and time appear to be more fundamental issues to design teams than say quality, for instance, yet given their importance there does not appear to be rigorous assessing of design options against each other on either basis.

7.10 WHERE DECISIONS WERE MADE

As well as defining the role of each discipline further insights can be gained into the level of interaction between design team members by considering where design decisions were made. Figures 7.23 – 7.25 show the types of meetings where system / sub-system design decisions were made. The key issue here is to assess the percentage of decisions that were made in isolation from the rest of the design team by a particular discipline. This includes meeting types 'working alone', 'informal conversation in the office' [with colleagues], 'in house meeting' [formal meeting in a specific company] and 'client instruction'.

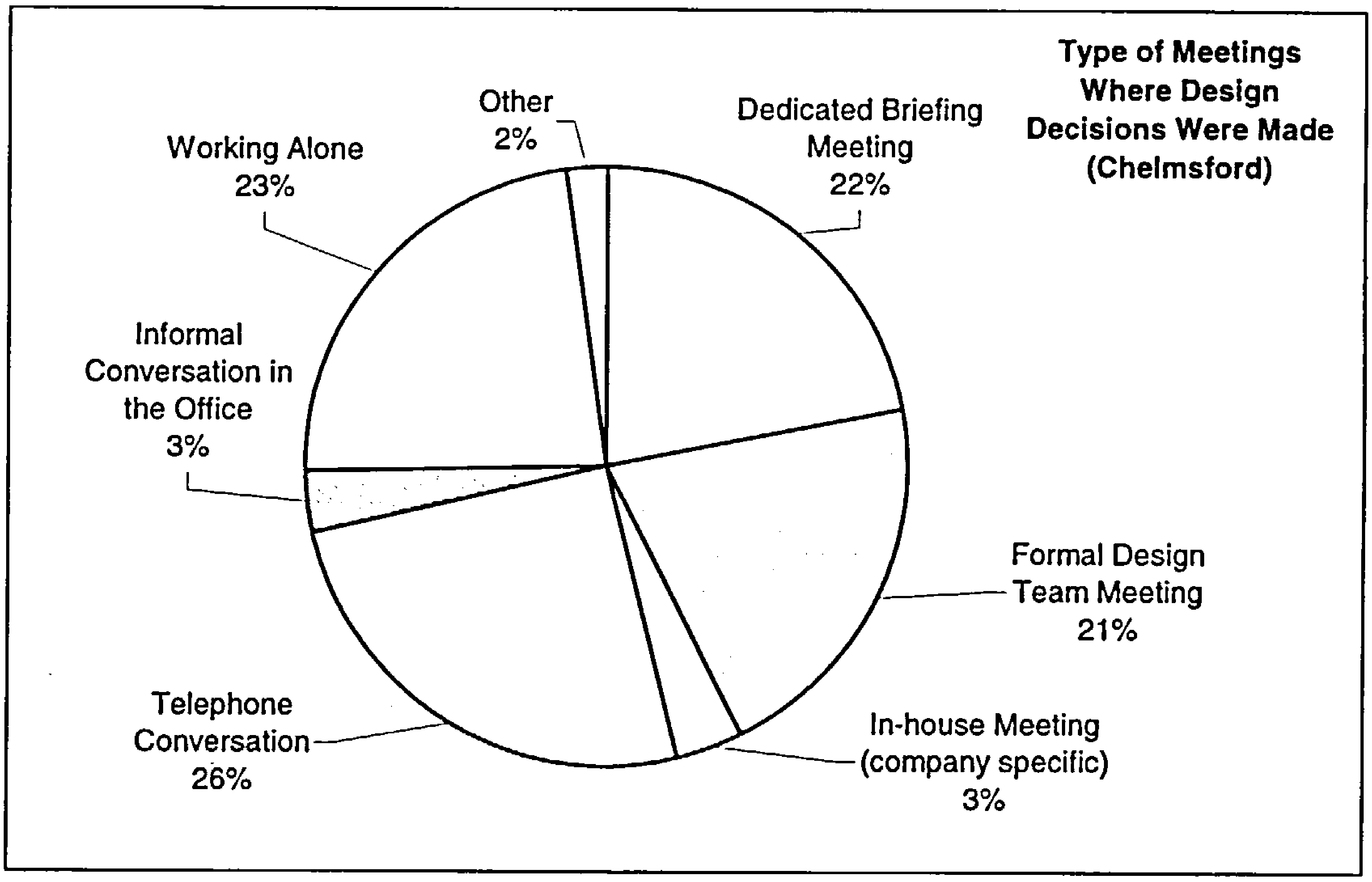


Figure 7.23 – The Types of Meetings Where Design Decisions Were Made (Chelmsford)

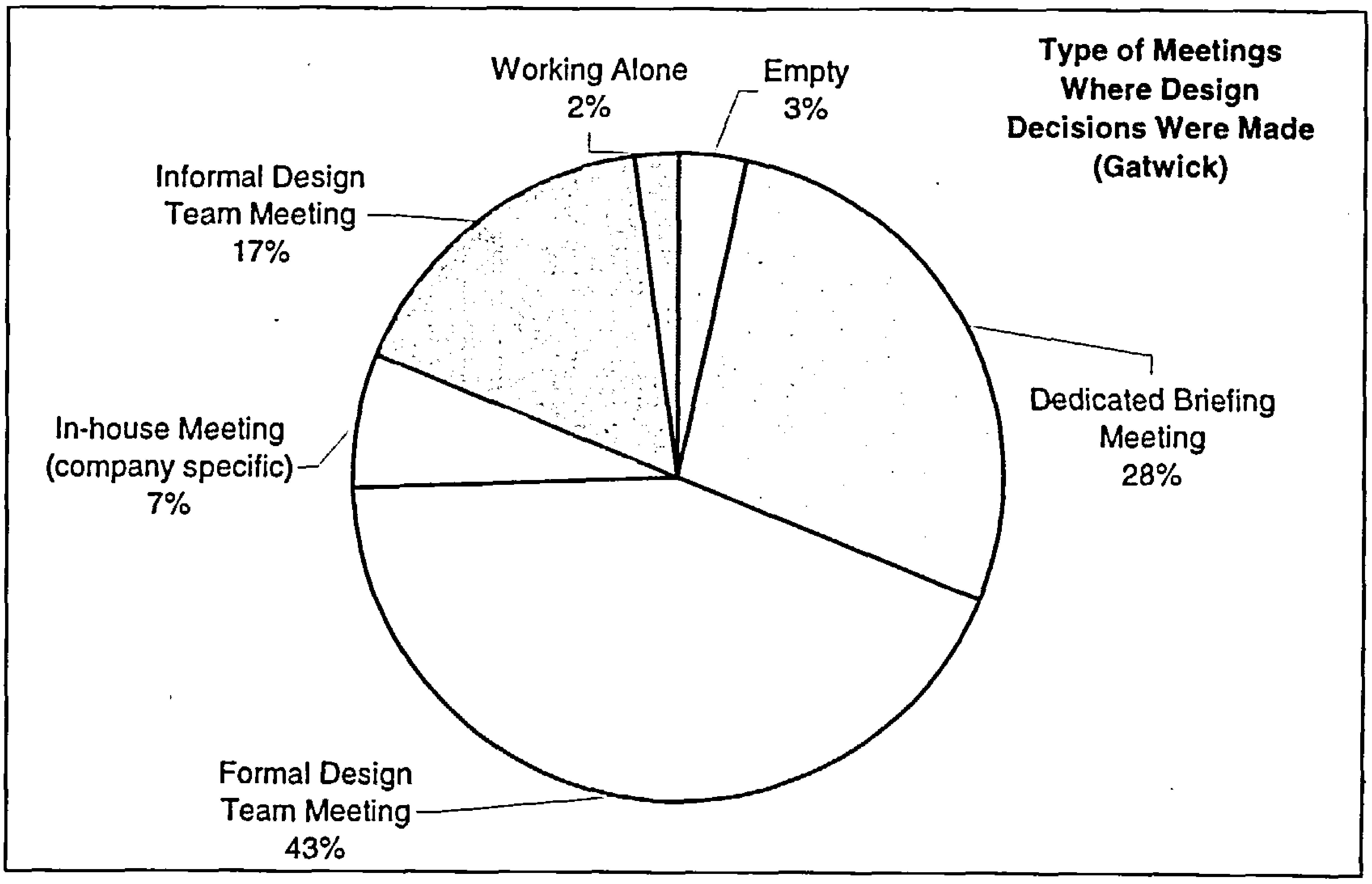


Figure 7.24 – The Types of Meetings Where Design Decisions Were Made (Gatwick)

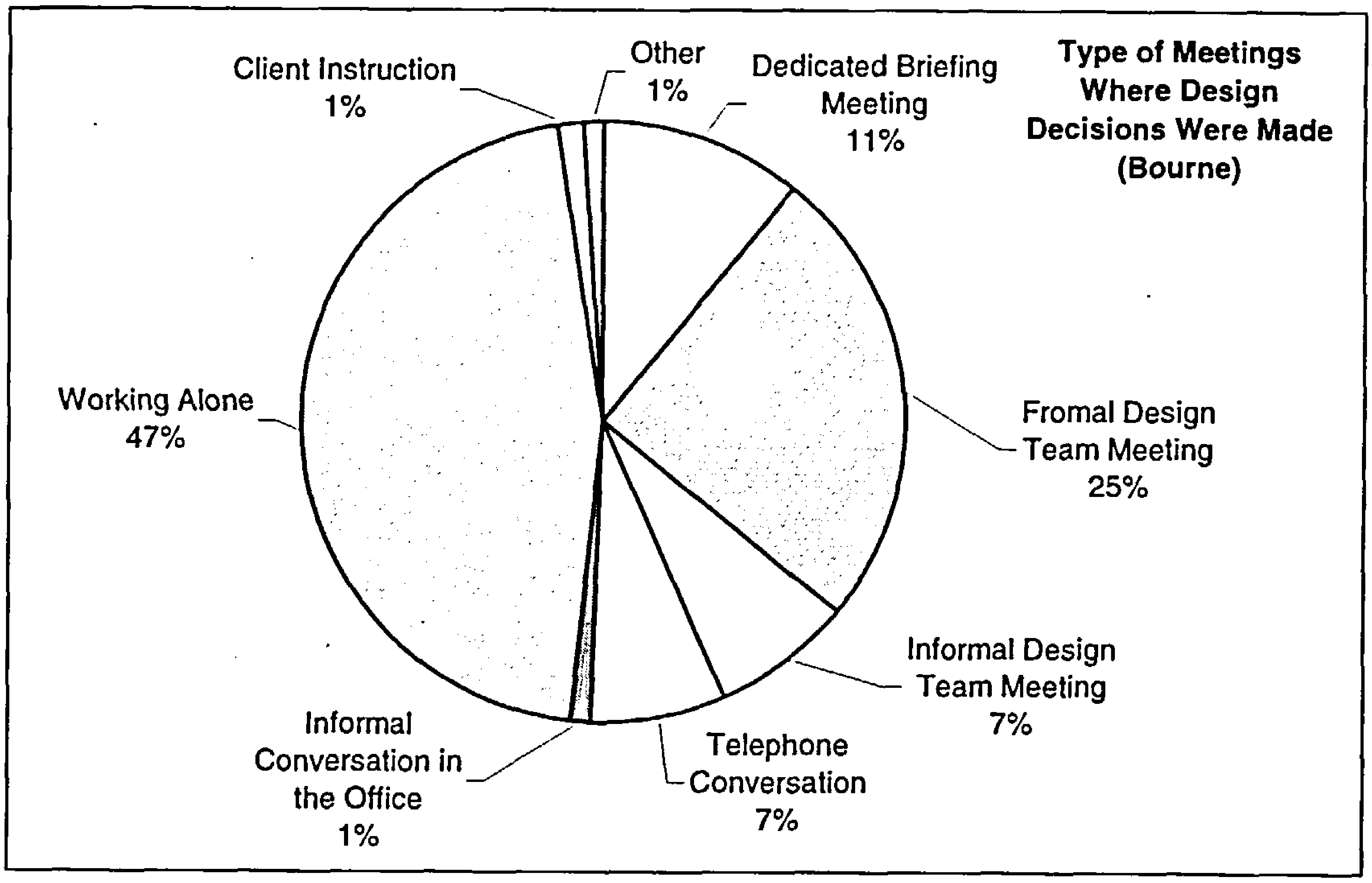


Figure 7.25 – The Types of Meetings Where Design Decisions Were Made (Bourne)

The other meeting types necessitate interdisciplinary interaction: 'dedicated briefing meeting', 'formal design team meeting', 'informal design team meeting' and 'telephone conversations'. Table 7.15 shows the ratio of the percentage of design decisions that were made in meetings attended by a single discipline and those which were multidiscipline (the categories 'other' and 'empty' have been omitted).

	Chelmsford	Gatwick	Bourne
Percentage of decisions made in meetings attended by Single disciplines: Multidisciplines	29 : 69	9 : 88	49 : 50

Table 7.15 - Percentage of Design Decisions Made in Meetings Attended by Single Disciplines / Multidisciplines

The figures show that the Gatwick project has a significantly higher proportion of decisions made at multidisciplinary meetings than the other case studies. In fact, its peculiar characteristic is that so few decisions are taken by individuals 'working alone', where as for Chelmsford it was 23% and for Bourne 47%. This again could be accounted for by the unusual contracting arrangements imposed by BAA. It is interesting to note, however, that the Gatwick team is not entirely co-located, although there is a project office which houses a number of disciplines. The Gatwick project also makes a significant use of formal meetings. An interesting characteristic of the Chelmsford project is the number of design decisions that were made as a result of telephone conversations.

7.11 INFORMATION NEEDS / SOURCES

To support the design decision making process designers make use of a variety of information sources. Figures 7.26 – 7.28 show the percentage of design decisions using particular information source types. By far the most commonly used information type in all three case studies is drawings, drawings produced within the scope of the project or pre-existing drawings. Table 7.16 shows the three most common information source types for each project.

	Chelmsford	Gatwick	Bourne
Information Source Type	Drawings Surveys Trade Literature	Drawings Trade Literature Design Guides	Drawings Design Guides Trade Literature

Table 7.16 – Most Common Types of Information Source Used to Support the Design Decision Making Process in each Case Study

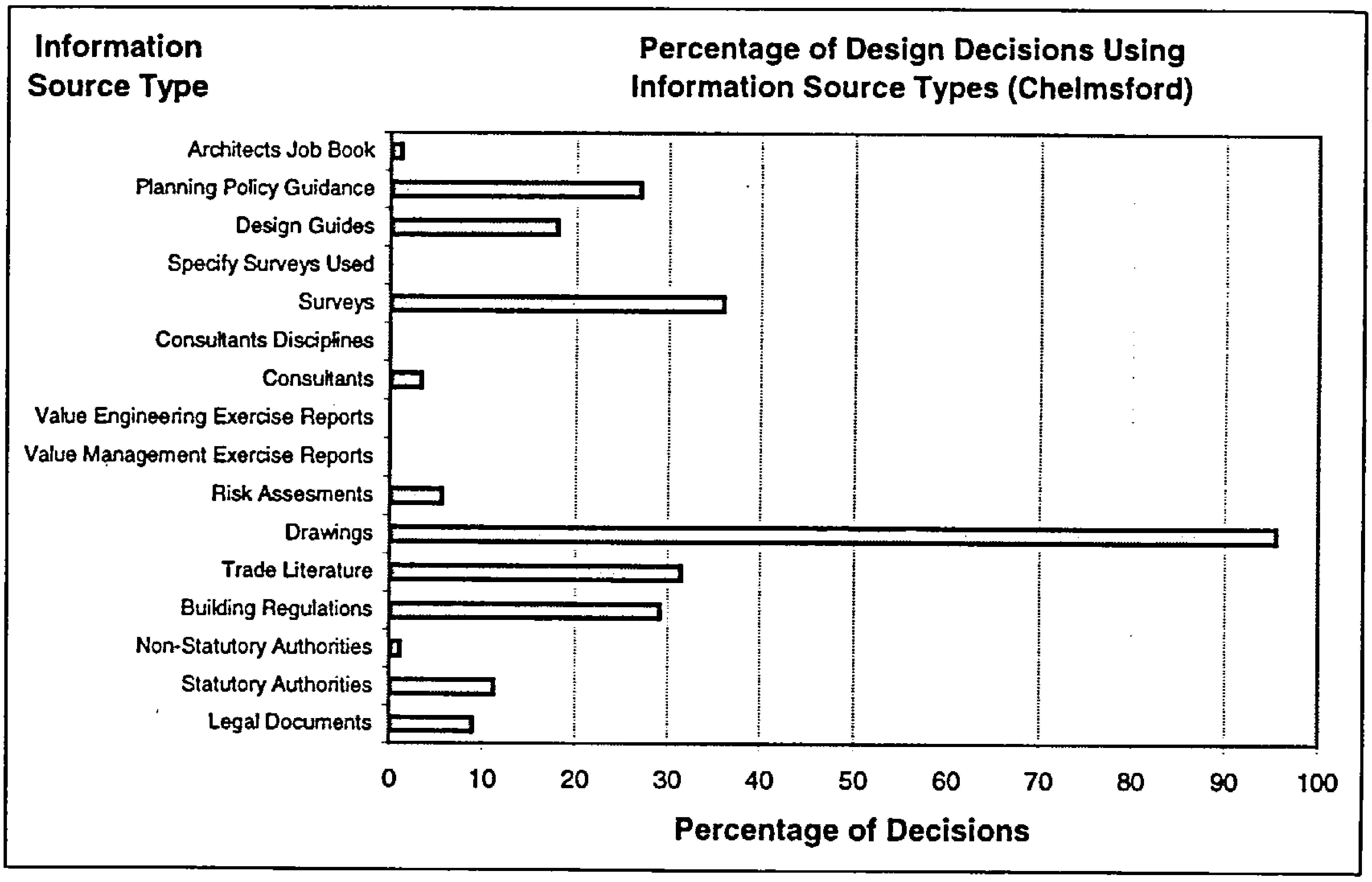


Figure 7.26 – Percentage of Design Decisions Using Particular Information Source Types (Chelmsford)

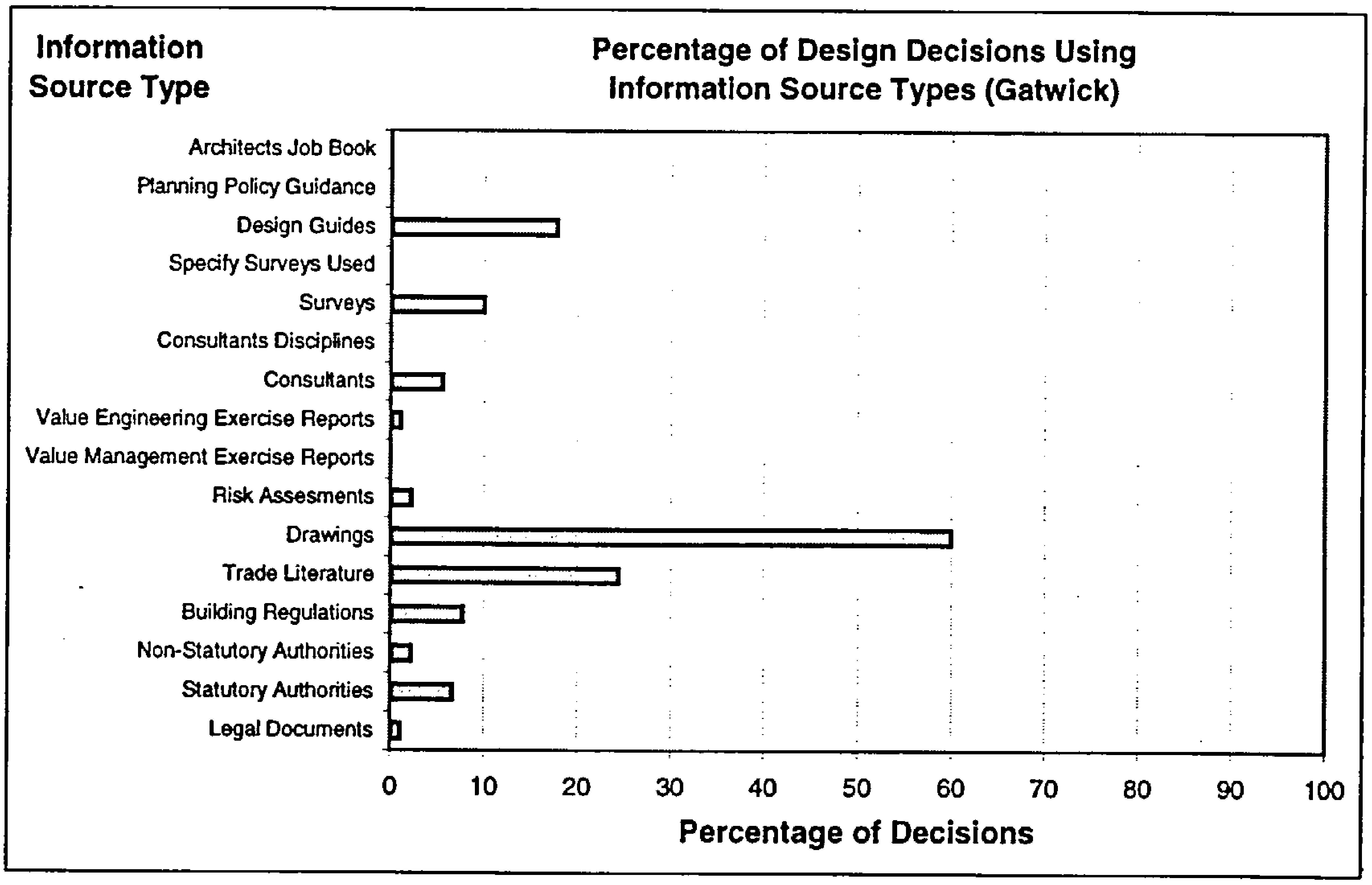


Figure 7.27 – Percentage of Design Decisions Using Particular Information Source Types (Gatwick)

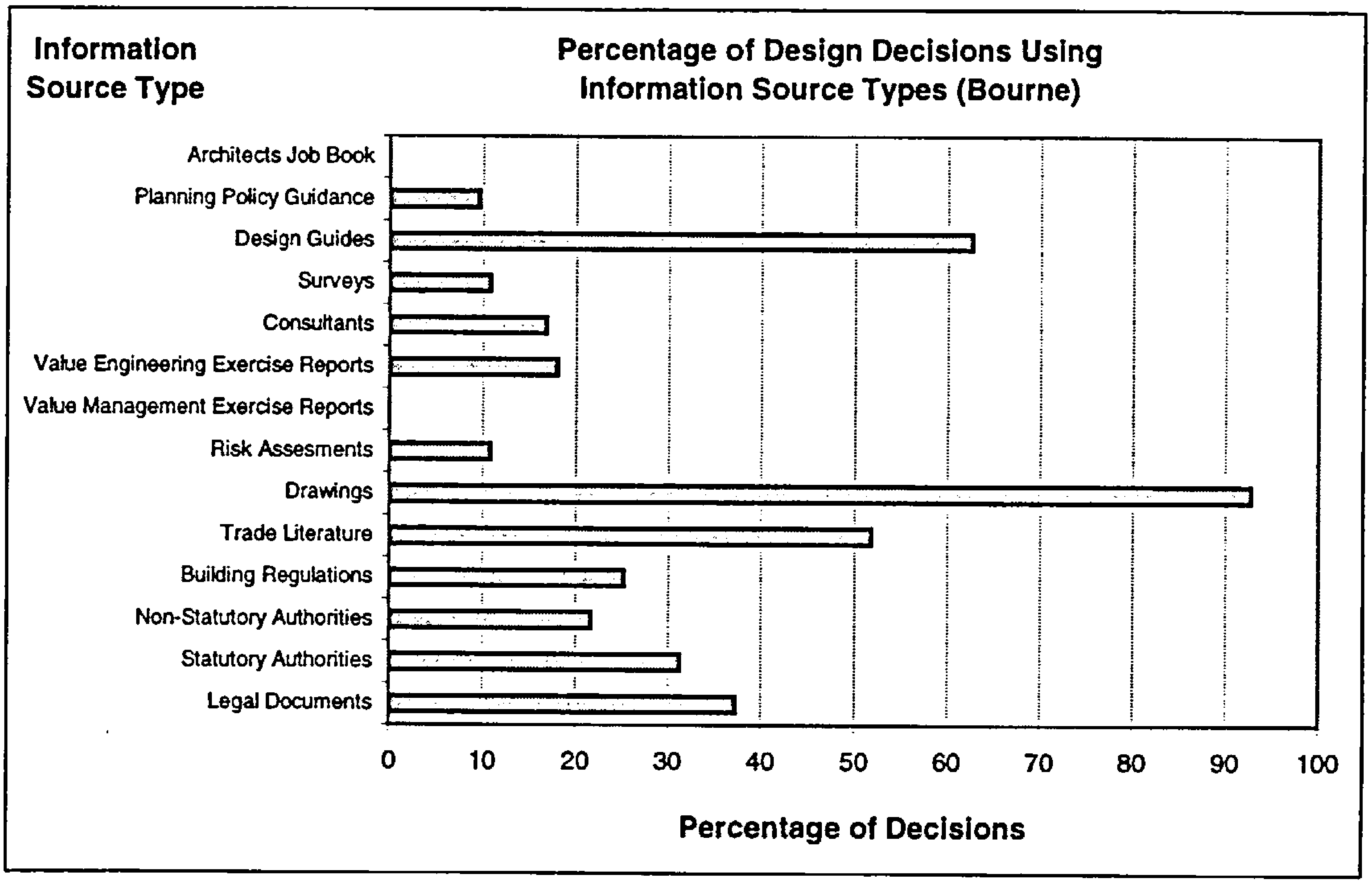


Figure 7.28 – Percentage of Design Decisions Using Particular Information Source Types (Bourne)

There is a remarkable similarity between all three projects, especially with regard to the use of drawings and trade literature. Design guides also feature as important information sources and in the case of Chelmsford so do surveys, planning policy guidance and building regulations. When considering the frequency of use of different information sources to support the decision making process, Bourne shows a higher degree of usage than the other projects.

7.12 INFORMATION TECHNOLOGY SUPPORT

Similarly, figures 7.29 – 7.31 show the percentage of design decisions using information technology types to support the decision making process. Table 7.17 shows the four most common types of information technology used to support the design decision making process in each case study.

	Chelmsford	Gatwick	Bourne
Information Technology Type	CAD Word Processor Telephone Fax	Telephone CAD Fax Word Processor	Telephone CAD Fax Word Processor

Table 7.17 – Most Common Types of Information Technology Used to Support the Design Decision Making Process in each Case Study

Unsurprisingly, perhaps, all three case studies use the telephone, CAD, fax machine and word processor as the main forms of IT / communication technologies when making system / sub-system design decisions. However, the percentage of design decisions that were stated as having used them varies quite considerably. Taking CAD for example: Chelmsford – 76%, Gatwick – 37% and Bourne – 96%. This variation also holds for the other IT types. Figures 7.29 – 7.31 also show that e-mail is still seldom used as a regular means of communication to actively support design. Another interesting feature is the lack of computerised analysis work performed and also the lack of favour of three-dimensional technologies.

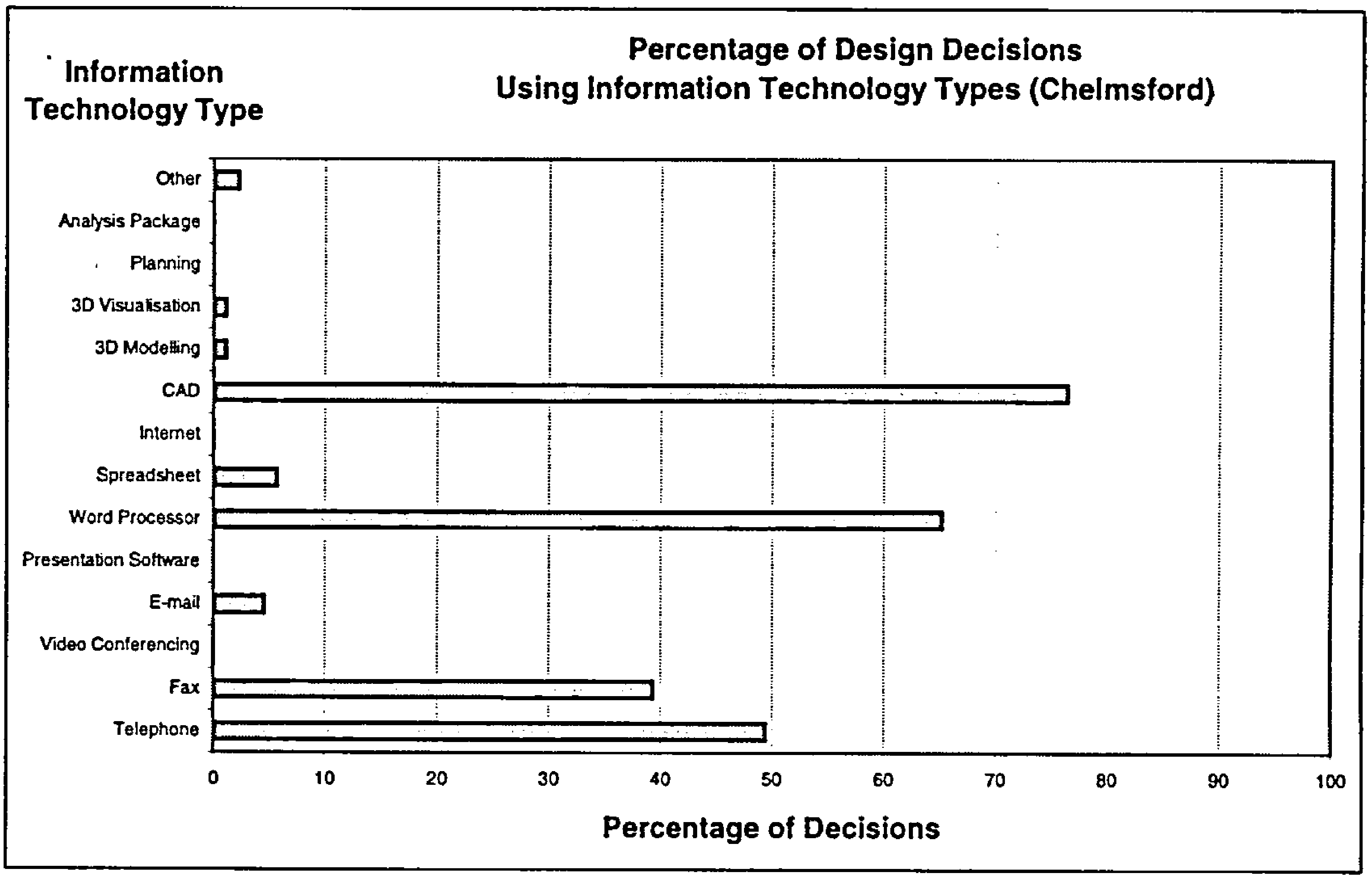


Figure 7.29 – Percentage of Design Decisions Using Particular Information Technology Types (Chelmsford)

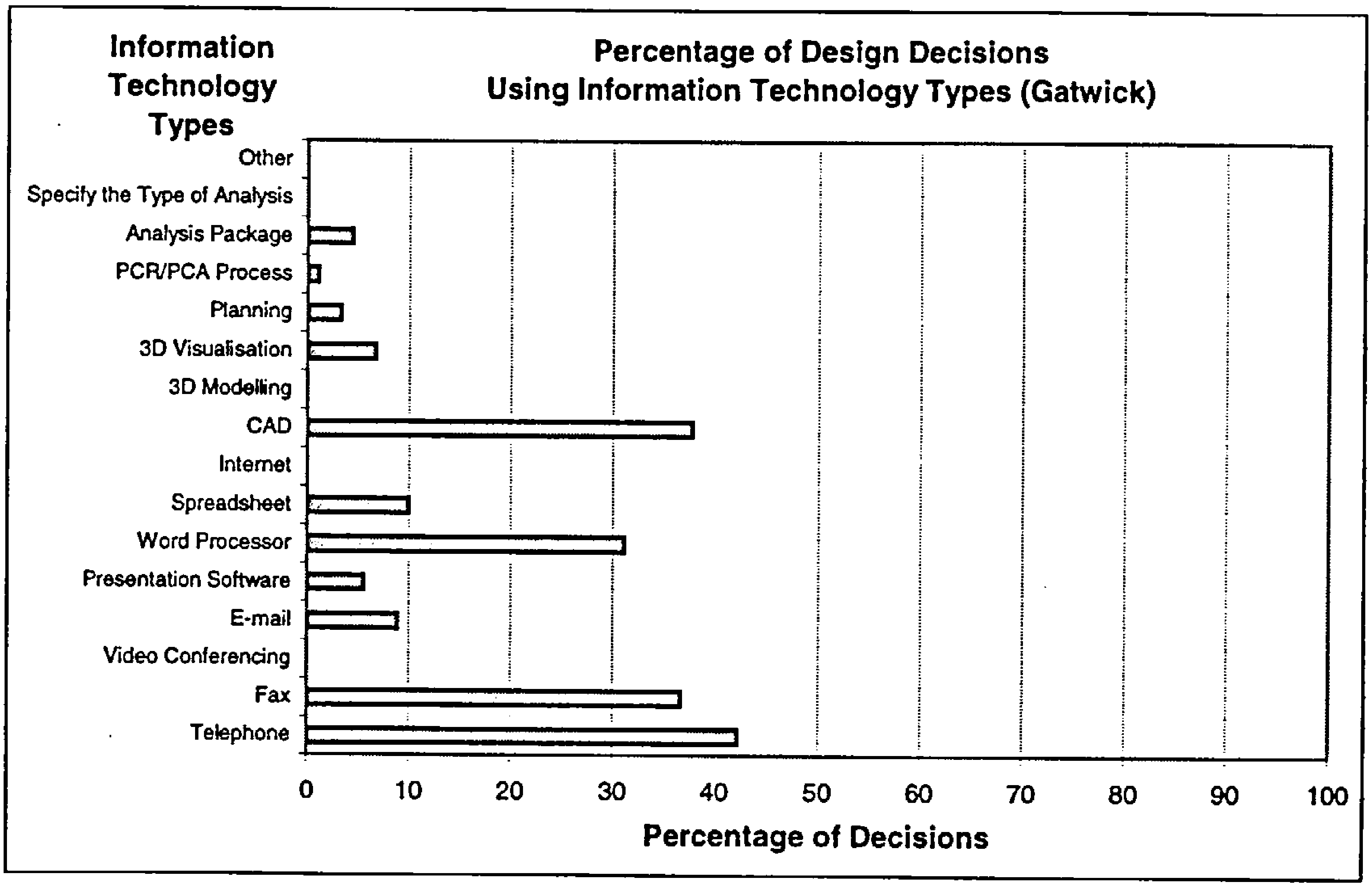


Figure 7.30 – Percentage of Design Decisions Using Particular Information Technology Types (Gatwick)

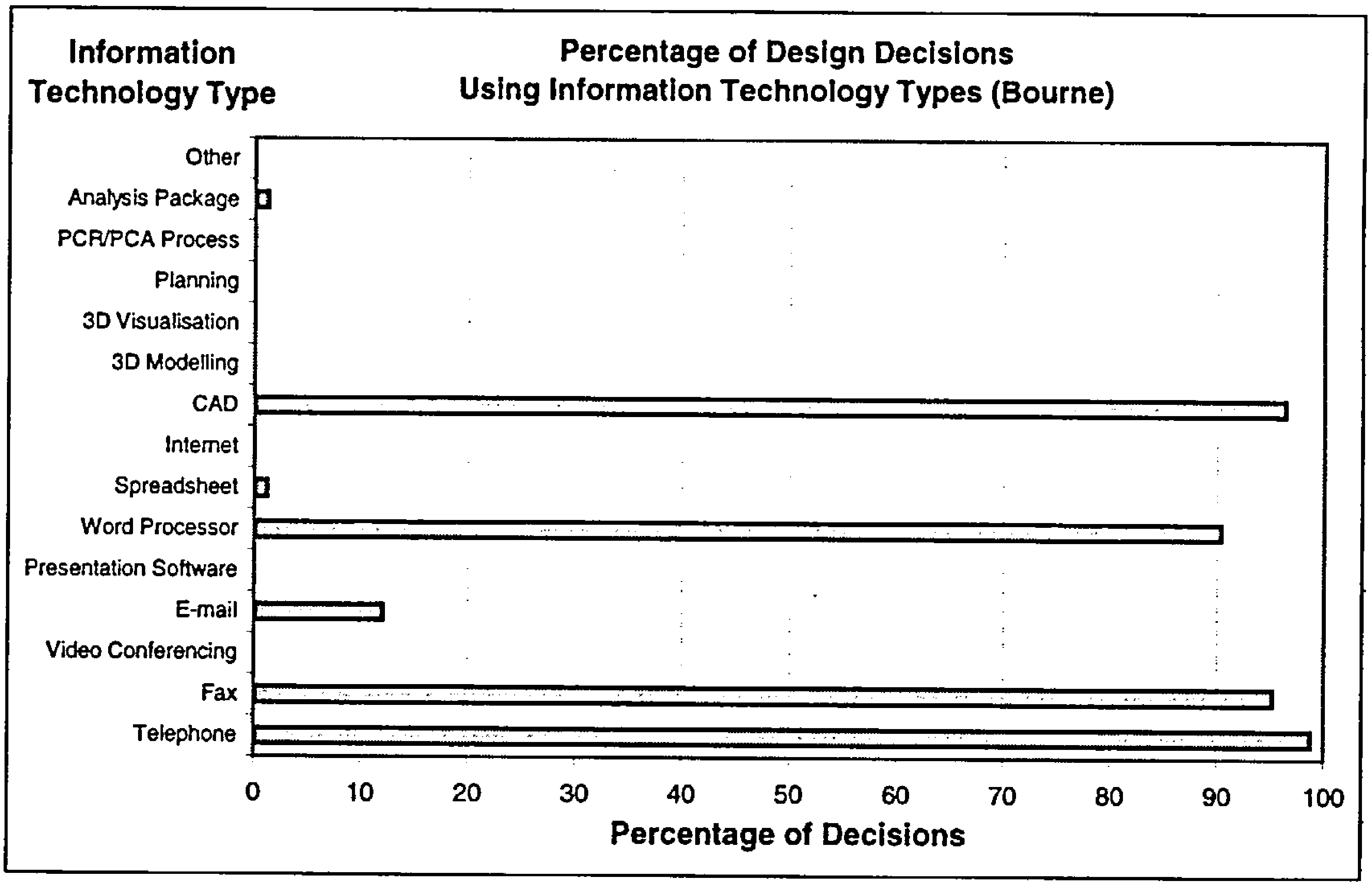


Figure 7.31 – Percentage of Design Decisions Using Particular Information Technology Types (Bourne)

7.13 THE ROLE OF THE DESIGN MODEL

The three case studies operated under different design management contractual arrangements: Chelmsford – slight variation on RIBA, Gatwick – BAA framework agreement and Bourne – flat fee for design feasibility (other design work carried out under design and build contract). Section 3.3 provides an explanation of the BAA and RIBA models. What is perhaps the most important aspect of each model is how it controls the design process. The BAA model controls the process by requiring an entire design stage to be complete before progressing on to the next. This has to be signed off by the client which releases money for the following design phase. To this end, the requirements of each design stage are very well defined. The RIBA model does not actually attempt to control the process in such a rigorous manner but rather indicates the type of activities that the client can expect from the designer at a particular point in time. It is a means of assessing when design bills should be paid and as such conceptually sits on top of an otherwise seamless process.

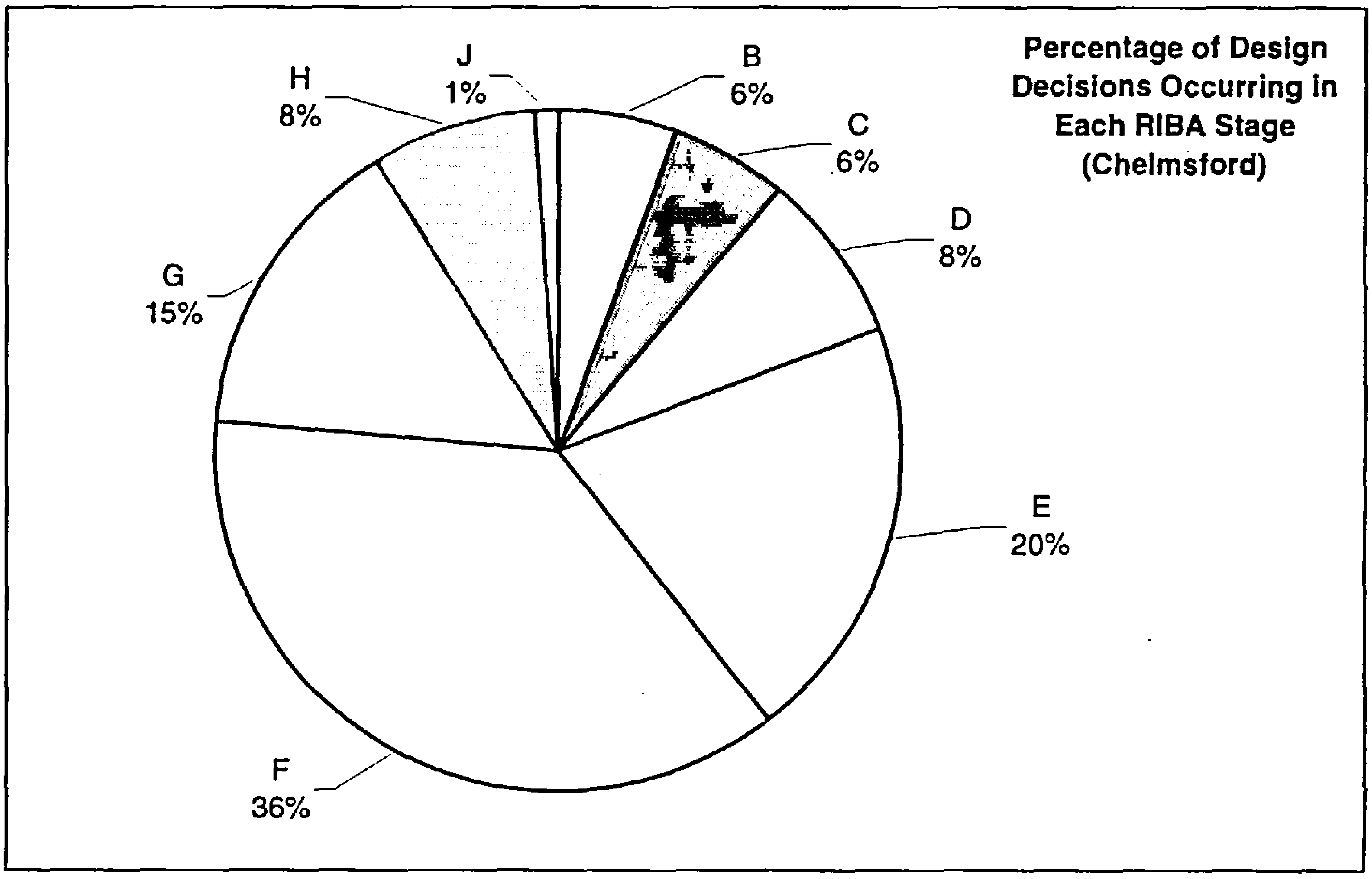


Figure 7.32 – Percentage of Design Decisions Occurring in Each RIBA Stage (Chelmsford)

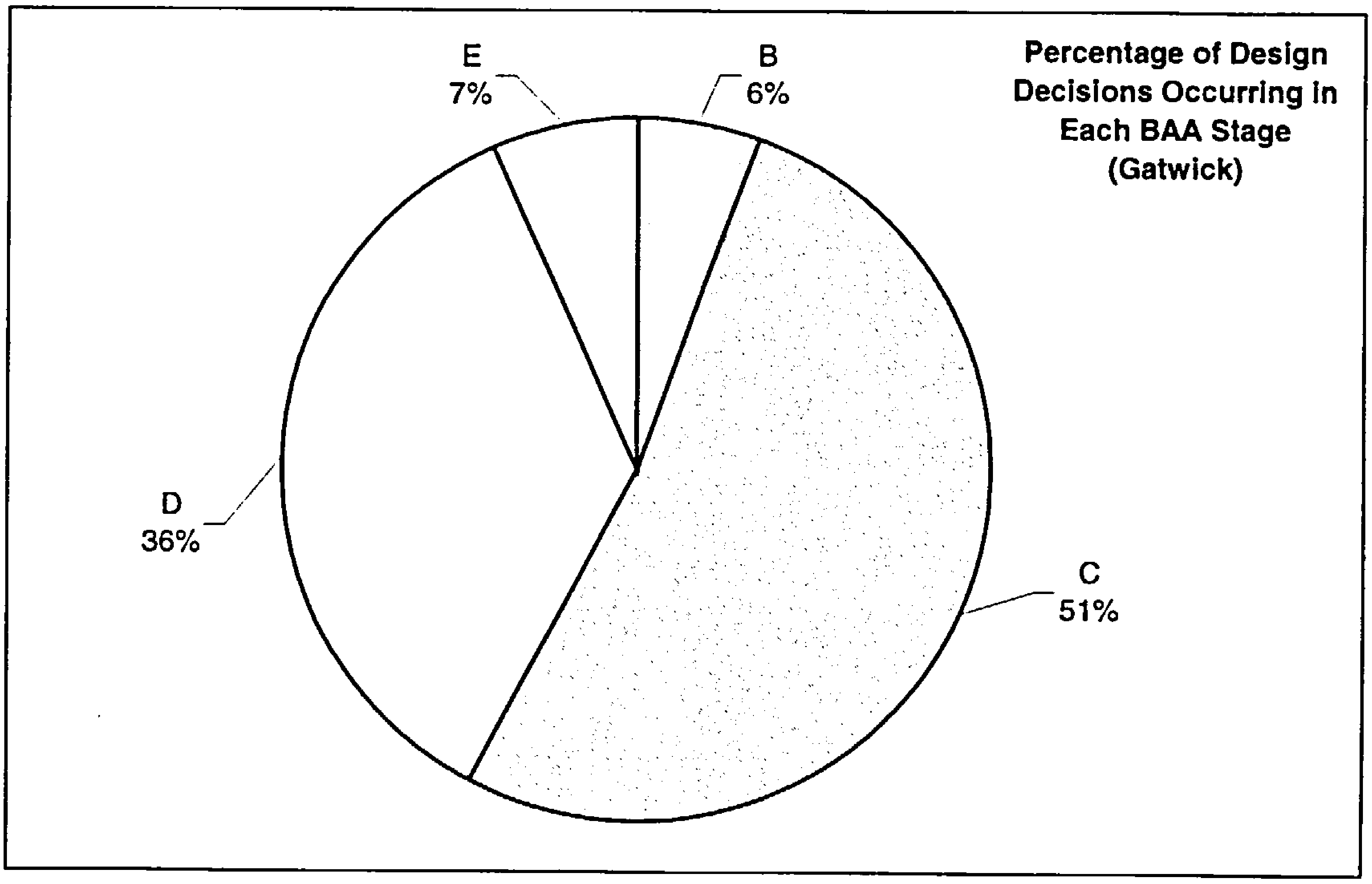


Figure 7.33 – Percentage of Design Decisions Occurring in Each BAA Stage (Gatwick)

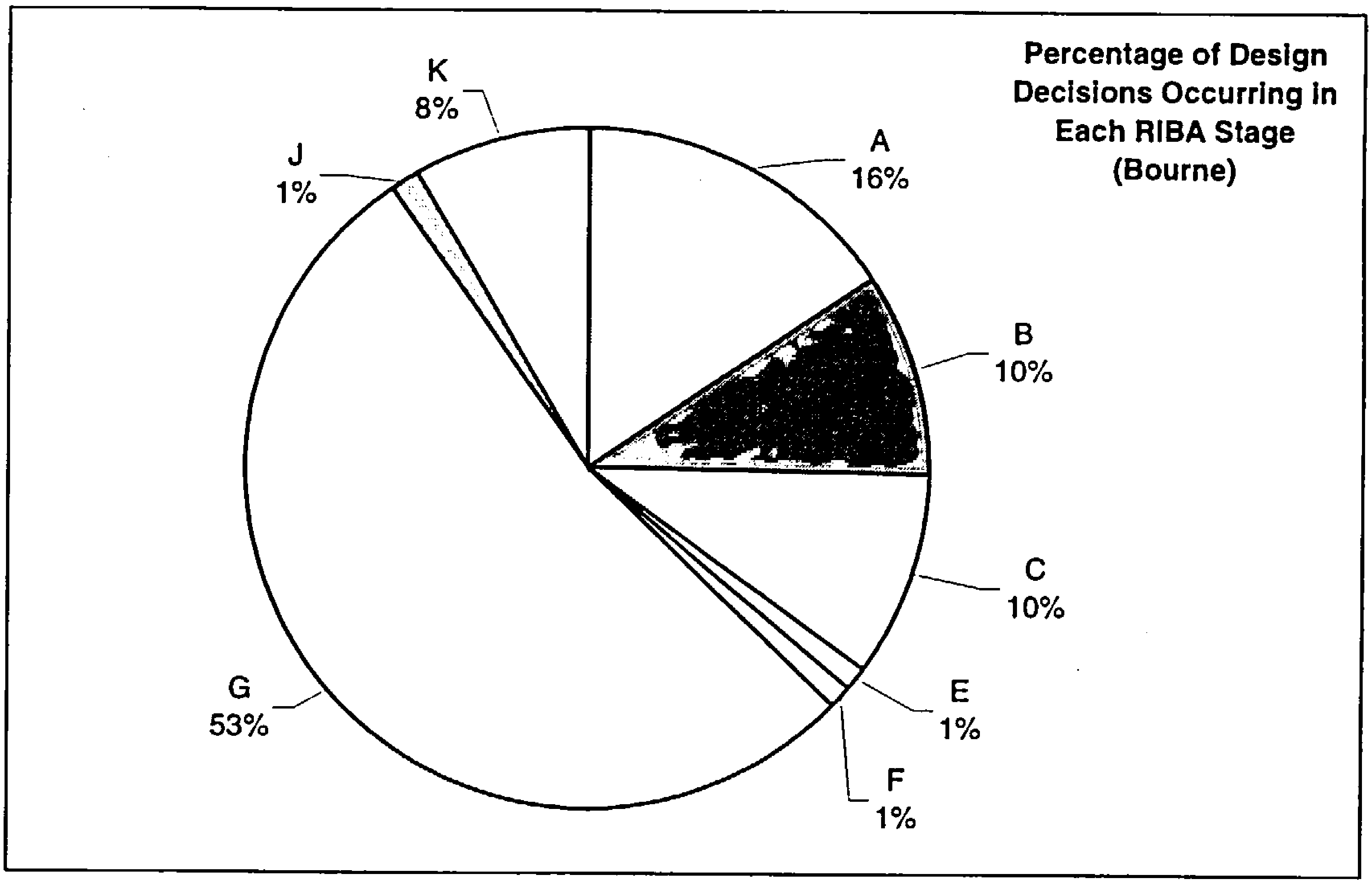


Figure 7.34 – Percentage of Design Decisions Occurring in Each RIBA Stage (Bourne)

Figures 7.32 – 7.34 show the percentage of design decisions occurring in each BAA / RIBA stage. There is considerable variation between the three projects which in part could be due to the different forms of contract under which the design work was commissioned. Another issue for Chelmsford and Bourne was that a number of design stages were overlapped because of the severity of the programme. This means that, when collecting data, rather than decisions falling into a particular design stage by virtue of the date that the decision was made, the data collector also had to consider the 'type' of decision that was being made and what stage it 'should' relate to. As there was no overlapping of design stages in the Gatwick project this issue did not arise. Indeed, it was the opinion of the author that the system / sub-system level design decisions would have been largely made as depicted by the Gatwick graph. Rather surprisingly both the Chelmsford and the Bourne projects suggest that a lot of the design decisions are made in RIBA stages E, F and G. To some extent this is because the BAA stages and RIBA stages are not directly equivalent (see section 3.3). Also, in the case of Bourne, there were two design phases which may have effected the way in which the decisions were categorised.

7.14 DISCUSSION

The application of the Electronic Data Gathering Tool (EDGT) to the three live construction projects was undertaken to map the design decision making process at the system / sub-system level.

The objectives of the study were to:

1. Identify the potential for standardising work – based on the generic content of the design decision process.
2. Map value generation from a design decision perspective.
3. Develop insights into:
    - The role of each discipline
    - Cost / programme visibility of designers
    - Constraints and reason drivers
    - Information sources used
    - Information technology used

The objectives were selected on the basis of trying to elucidate some of the issues involved with application of lean thinking to construction design.

7.14.1 Design and the Design Process

Design can be considered to be a mixture of value generation – design decisions and design process – the tasks performed to identify and test constraints, devise options and ultimately provide sufficient information to the designer to make an informed decision. It might be argued that the creation of design options is in itself value generation, however, from the product's perspective only those options that are selected to fulfil a particular functional requirement actually add value. All rejected options, although an integral part of the decision making process, add no value to the product if they are not included. They may be considered to add value indirectly in that they served the purpose of helping the designer select another option by testing design constraints, however, this is an incidental factor as a designer could have arrived at the same decision without needing to create and reject a particular design option.

The *value stream,* according to Womack and Jones (1996), is all the activities / tasks required to bring a particular product through the three critical management tasks: problem-solving, information management and physical transformation. Mapping the stream means identifying all of those tasks both inside the organisation and beyond in the supply chain. Having mapped the tasks they are then split into three categories:

1. Tasks which unambiguously add direct value to the product.

2. Tasks which add no value to the product but are unavoidable with current technological limitations of the production processes / technologies.

3. Tasks which add no value to the product and are immediately avoidable.

Recording the design decision making process is in fact a subset of mapping the value stream. Design decisions directly add value to the product and therefore can be considered to *generate value.* These are necessary and, of themselves, do not constitute waste in the design process. However, it is important to distinguish between the decision being made and the way in which a particular decision is arrived at, as the latter maybe performed in a wasteful manner. The value stream maps are useful for their ability to identify and remove waste in the process at the task level, however, the value generation maps represent the leanest form of design, as design decisions are by definition the part of the design process that adds direct value to the product. The maps do not define the steps necessary to make those decisions, however, as many routes may be taken to make design decisions with varying degrees of efficiency.

7.14.2 Generic Design: Standardising The Design Approach

A key issue identified in the literature survey to applying lean thinking to the new product development process, which is analogous to construction design, is the idea of following a standardised procedure. The author therefore hypothesised that the kernel to the successful application of a standardised approach to design lies in the generic content between design projects. The usual statement from construction professionals is that 'every project is novel' which of itself suggests that it would be impossible to devise a standardised methodology. Indeed, design professionals are so entrenched in the belief of the uniqueness of each project that there is an air of disbelief that effective design planning is possible (Coles, 1990). In his desire to see improvements in the construction design process, Sir Michael

Latham (1994) advocated the use of design checklists. This is a form of standardisation which he envisaged would unambiguously define responsibilities for each of the design disciplines. The advantage of checklists is that they also provide a form of retrospective monitoring, with the "Have we done..." type enquires. Latham (1994) stated that a 'checklist of the design process was required', which suggests that the checklist would operate at the task level, defining what each discipline was required to produce / co-ordinate. It would seem in practice that his idea was never realised as none of the projects studied used this approach. It was also evident that in two out of the three projects little formal design planning was undertaken. Both Chelmsford and Bourne only produced Gantt charts to indicate the approximate timing of each design stage and the main activities proposed. The Gatwick project, however, had a far more rigorous approach which involved process mapping each design phase, identifying to a detailed level the tasks involved and the interdependencies that exist between them. This was accompanied by the idea of design 'fixities' which act to freeze parts of the design after particular design decisions have been made. This means that the input information into successive tasks will not change and therefore the designer can work more confidently. The Gatwick project also had an explicit design philosophy to make use of standardised components and approaches wherever possible. Interestingly, this was not reflected in the reason drivers that were used to choose between options at the system / sub-system level (see figures 7.17 – 7.19). It may have been argued that this philosophy would be more apparent at the detailed level, except that the Bourne project, under a design and build contract, had standardised components and approaches ranked as the fourth most common reason driver for selecting particular design options.

To establish the generic content at the system / sub-system level design decisions were recorded in the three case studies and matched to each other. It was found that between 73% - 80% of the types of decisions that are made in construction projects are generic. These decisions were found to be made in different orders and at different times during the design process (see figures 7.5 - 7.7). This suggests that although there is a large generic component of design decisions, there is also a large degree of variability in how and when these decisions are made. This alludes to the possibility of establishing an approach to planning and monitoring construction design which ensures that designers consider all the decisions which have to be made, the timing and ordering of the decisions, whilst not prescribing a rigid route that does not allow for those aspects of the project which are indeed unique. This approach could incorporate Latham's (1994) idea of clearly defined design responsibilities by assigning each decision to be made to a particular discipline. In its simplest form this would be a list of decisions to be made, the timing of the decision (and hence the order) and name of the person responsible for making the decision. This could be developed further by adding in the tasks which are needed to be performed to make that decision, the information to be gathered and the tools which should, or could, be used to support the decision making process. All these components could be based on the value generation maps produced in this study. The decisions which have been found to be generic would provide a starting point, with project specific decisions identified by the design team. At the same time the design team would have to work out the timing, order and responsibility for each decision based on a mixture of experience and tools - Design Structure Matrix (DSM) for example. Monitoring progress against planned activity would provide a process performance metric which could be used as a basis for discussion for project managers. A long-term consequence of using a tool developed on this basis is that individual designers may elect to follow the same decision pattern regularly to help them control the process better. This would leave more time and energy to concentrate on the truly creative aspects of construction design, as the approach to design, not design itself, would become routine. This is one way in which a standardised approach to construction design could be achieved without inhibiting architectural freedom. This would lead to a better controlled design process, not 'controlled design'.

Further mapping of the tasks involved for each decision could be employed to establish the value stream. This would help identify waste in the design decision making process and could lead to a more efficient configuration and organisation of design tasks. Due consideration to Ballard & Koskela's (1998) view of design as conversion, flow and value may be appropriate for this task.

7.14.3 Design Team Interaction

An important factor in the implementation of lean thinking to the product development process, and concurrent engineering, is the use of co-located multidisciplinary teams (Womack and Jones, 1996) – see sections 2.2.4 and 2.31. The teams described often include product designers, production engineers, purchasing staff, tool designers and marketing personnel. Whilst the higher volume manufacturing companies may have different needs to construction project teams, however, there is a noticeable lack of construction input in the early design stages of all three projects. This is a very important aspect of the lean thinking paradigm. The Gatwick project seems to be closest to the lean thinking 'ideal' with the BAA framework agreement making a number of disciplines available for consultation. However, the set up falls short of a co-located team and it can be seen from figure 7.9 that the product designers make nearly all the system / sub-system level decisions. On this basis, Chelmsford fairs worse than Gatwick but Bourne, under the design and build contract, has slightly more production input at this level. None of the teams were co-located, although the Gatwick project did have a project office housing some of the disciplines. However, the biggest deficiency with respect to the lean thinking 'ideal' is the lack of consistent production input throughout the early design phase. In the Chelmsford project more than 80% of the design decisions were made by just two disciplines: architect and client.

Considering figures 7.11 – 7.13 it can be seen that the Gatwick approach did inspire more collaborative design with each of the main disciplines getting involved in higher percentage of the design decisions, with the exception of the architect. It would seem that the type of contractual conditions may have an impact on the way in which the design team interacts. It most certainly has an effect on the timing of appointments which can mean the absence of specialist knowledge at crucial early design stages. Interestingly, in all three projects, the client representatives played a significant role in the decision making process. This is likely to be due to the clients' levels of experience and sophistication. Another interesting discovery from the data is that the quantity surveyor makes few or no design decisions at the system / sub-system level. The role of the quantity surveyor will be discussed further in section 7.14.5.

7.14.4 Constraints and Reason Drivers

To be able to improve construction design an understanding of the reason drivers that designers are using to choose between options is absolutely necessary. These reason drivers must also be viewed within the context of design boundaries, or constraints, within which designers are operating. What was most interesting from this study was the amount of commonality shown between the projects. Given that the projects are very different in terms of building location, usage, client body, procurement route, etc, yet three of the top five constraint types feature in each case study: D – 'physical constraints', F – 'interfacing issues' and L – 'building regulations / planning authority influence / standards'. Two further constraint types feature in the top five of two pairs of case studies: K – ' functional issues / fitness for purpose' and I – 'economic issues', with M – 'client requirements / preferences' and B – 'end user requirements / preferences being important for two individual case studies.

With regard to the reason driver categories, or types, there is a very similar situation to the constraints. All three case studies include reason categories F – 'interfacing issues', I – 'economic issues' and K – 'functional issues / fitness for purpose'. Chelmsford and Gatwick have H – 'buildability' and Gatwick and Bourne have M – 'client's requirements / preferences'. Chelmsford and Bourne also have L – 'building regulations / planning authority influence / standards' and J – 'utilise standard components / approaches', respectively.

Simple inspection of the constraint categories and reason drivers suggests that they are well matched, however, noticeable omissions from important categories include both quality and time issues. This is very interesting especially as all three projects were considered to be on a tight schedule yet this was not reflected in the decision making process in the constraints or reason drivers. This may mean that designers do not fully understand the relationship of decision making with the impact on programme. This was found to be the case in section 7.9 and is discussed further in section 7.14.5. There is obviously an awareness within the design team of the importance of pressing deadlines, however, the problem seems to be that there is an inability to translate how selecting particular design options can ease or intensify time pressures. This may account for why The Agile Construction Initiative (1998) found that three quarters of projects will experience delayed completion. Quality is an important issue that will effect client satisfaction yet it rarely featured as an explicit constraint and never as an explicit reason driver. This could be that quality issues are deemed to be more important at the detailed level – 'the devil is in the detail'. If this is so, it appears to be a grave oversight on the part of the design teams. It maybe that quality was more of an implicit characteristic that, because of its somewhat nebulous nature, was not discussed explicitly, or explicitly within the term 'quality'. It could also be reflective that of time, cost and quality, cost is by far the most important issue.

A further insight gained relates to the importance of buildability. Although specified as an important reason driver when comparing between options, there does not appear to be a means of assessing and comparing the buildability of options, save the experience and knowledge of the design team and external consultants. What is also important from a lean perspective is that reason drivers also include 'process issues'. That is, designers should choose between options not solely on a functional basis but include issues such as 'use of standard components / approaches' and 'speed of construction'. From a client's point of view, the 'fitness for purpose' issues are an absolute necessity to meet the functional requirements. From the designers' perspectives, process issues are crucial for their competitiveness and the long-term survival of organisations. Also, the more 'buildable' the option the less waste there is likely to be in the total construction process. This helps to make the product delivery process leaner.

7.14.5 Cost & Programme Visibility

Figures 7.20 – 7.22 are an attempt to show the cost visibility that the designer had at the time of making design decisions. That is was the designer able to quantify the impact that the decision would have on the project in terms of cost when choosing between different design options. If the designer was able to assess the cost impact for every decision then the 'actual' curve for each case study would be the same as the 'ideal' curve. The ideal curve is simply the cumulative count of decisions made expressed as a percentage of the total number of decisions. Because of the quality of the data recorded the 'actual' curves represent an enhanced cost visibility. The 'real' cost visibility is somewhat less than the graphs show. This is largely due to the fact that the data supplied often came from cost plans produced by the quantity surveyor. These cost plans were either early estimates prior to a particular decision being made or refined cost plans, refined on the basis of having made the particular decision. This means that the quantity surveyor is acting in a cost controlling capacity and is not fully integrated into the design decision making process. This knowledge presents a real opportunity to redefine the quantity surveyor's role from cost controller to one of assessing value or value for money of each design option considered. One of the issues that will arise from this suggestion is who will employ this 'value for money assessor' as the role of cost control will still be desired by construction clients. Therefore, it might require design companies to have this role in house or for this role to be contracted as a new discipline within the design team. There is some support for this position within the literature as Atkin (1998) suggests that the role of the quantity surveyor is not well integrated into the design process, and Johnson (1992) that most existing cost evaluation paradigms focus on assessing costs after design decisions are made. Exploration of values and preferences should be the major focus of economic analysis. The Tavistock Institute interim evaluation report, 'Building Down Barriers' (1999) states that there is a need to be able to make rapid generation of reliable costings for design options in early design stages. This could be facilitated by tools which may have to be developed and / or a redefining of the quantity surveyor's role.

From the data gathered it was even more apparent that the programme visibility of designers is lower than the cost visibility. This is shown to be the case in the data directly relating to programme visibility and also in constraints and reason drivers (see section 7.14.4). To expand upon the need to be able to rapidly generate reliable costings of design options, there also needs to be a means of comparing options on a time basis. This could include lead times for availability of materials and assembly time. These issues are also very closely related to the idea of buildability. Indeed, a future research project could be to devise an integrated system which allows the designer to simultaneously compare options on the basis of cost, construction time and buildability.

In lean design environments project teams are told to aim for a target cost which is determined by estimating a market price (what the market will bear) and subtract an acceptable margin. The team then designs the product such that the cost will not exceed the target cost minus the margin. This pricing strategy is obviously suited to highly competitive consumer markets. In construction projects budgets are initially based upon a price per square foot from experience of previous buildings of a similar type, office blocks for example. The price is then firmed up as design progresses and the client's exact requirements are established. This approach does not really consider what the market *will* bear but rather looks retrospectively at what it *did* bear. The domestic industry should exercise due care that the more demanding client's do not begin to look towards international players to increase competitiveness in the market.

7.14.6 Design Support

For the purposes of this study design support refers to the information sources and IT that were used to support the design decision making process.

By far the most used information source type to support the design decision making process was drawings. Trade literature, surveys and design guides were also seen to be significant. Value engineering reports were also used in both Gatwick and Bourne, with Bourne using them in nearly 20% of the decisions made. Value engineering is a proven technique used to identify alternative approaches for satisfying the requirements of a project whilst lowering cost and ensuring technical competence in performance (Acharya et al, 1995). Using the approach is likely to bring an equivalent or better product for a lower cost, however, it does not necessarily make the design process more lean, but should certainly be considered as a tool to be used in a lean design environment.

The most common IT and communication technology types that were used to support the decision making process are the telephone, CAD, fax and word processor. The word processor and fax have a link in that a number of faxes were sent directly from computers with the text generated in a word processor package. CAD is used to generate a high percentage of drawings (see table 7.9) and given that drawings are most often used to support the decision making process and the means by which engineering data are conveyed, it is unsurprising that this technology was commonly used to support the process. What is surprising is that e-mail was not used more often to communicate between parties and the lack of use of three dimensional technologies. In none of the decisions was the internet used to support the decision making process. This suggests that either the internet has net yet matured into a useful tool for design purposes or that the perception of its usefulness is very low.

7.14.7 SWOT Analysis: Research Approach

One of the novel features of this research was the approach taken to investigate the design decision making process at the system / sub-system level. For this purpose the Electronic Data Gathering Tool (EDGT) was developed and used on three live construction projects. As a means of establishing the credibility of the results and the usefulness of the approach a SWOT (Strengths, Weaknesses, Opportunities and Threats) was performed (see figure 7.35).

A particular strength of the approach was access to objective data for three disparate case studies from two of the industrial partner companies. The case studies were all live projects which means that the issues recorded were still current for the design teams. This was facilitated by regular contact with an individual intimately involved with the decision making process for each project. This contact and the design of the EDGT provided insights into a number of areas of the design decision making process including the decisions made, timing of decisions, options considered, constraints, design support – information sources and IT. The information was recorded over a number of months which allowed a significant amount of data to be compiled. The data was also stored electronically in a form that eased the data processing stage of the study. The research has led to sufficient insights into the design decision making process so that it has been possible to make suggestions as to how to make steps towards lean design. These include better design planning, improving cost and programme visibility when choosing between design options which in part could be achieved by redefining the role of the quantity surveyor from cost controller to value for money assessor.

A weakness of the study was that it was only possible to investigate three case studies because of the resources required to gather the data. This means that it is difficult to make generalisations about the findings. Case studies were used rather than a statistical sample as the key factors relating to design decision making in construction design projects had not been previously identified. Hence, there was little value in guessing at a small number of factors / variables and investigating them with an appropriate statistical sample, when using the case study approach allows a larger number of issues to be considered, although is unlikely to provide sufficient evidence of causality beyond the examined data. Case studies are therefore better suited for the purposes of providing first insights into the decision making process. When matching equivalent decisions across case studies there was a problem of semantics which had to be overcome. This was achieved by getting the data collectors to match their decisions to each other's case study. Another potential problem, although one that was never realised, was that data collection would have been severely hampered if the data collector had became unavailable for some reason, as there was a learning curve for those involved in the research.

Strengths

- Depth of study
- Breadth of study
- Access to objective data
- Diversity of case studies
- Data captured electronically
- Provides insights into application of lean thinking to design
- Availability of researcher during data collection phase

Opportunities

- Make recommendations for steps towards 'lean design'
    - Change role of Quantity Surveyor from cost controller to value assessor
    - Highlight generic design content
    - Improve design planning on a design decision basis (or value generation basis)

Weaknesses

- Limited number of case studies
- Difficult to make generalisations
- Amount of effort required to collect data
- Difficulty in matching equivalent decisions

Threats

- Data collection not completed in time
- Unavailability of project data collector
- Unavailability of suitable projects

Figure 7.35 – SWOT Analysis on Research Approach

7.15 CONCLUSIONS

A study into the design decision making process at the system and sub-system level was conducted. The Electronic Data Gathering Tool (EDGT) was used on three live construction projects to gather data for the investigation. The projects were nominated by the industrial partners Stanley Bragg Partnership and Taylor Woodrow Management Contracting.

The main findings of the investigation are as follows:

1. There is 73 – 80% design decision commonality across projects at the system / sub-system level. These decisions were made in different orders and at different times during the design process. This means that the timing and ordering of decisions is variable. This knowledge can be used to produce a design planning method that will move the design process to a more standardised approach, that is, a more standardised process, not standardised design. Having planned design, measuring progress against intention produces a useful metric (see chapter 8).

2. There is limited cost and programme visibility when choosing between design options when making a particular design decision. That is, the designer is not able to assess the cost and programme impact of selecting one option over

another. This inhibits the ability of the designer to make an informed decision - this needs to be addressed.

3. Related to finding number two is the role of the quantity surveyor within the project. The current role is one of cost control rather than active participation within design process. Cost visibility maybe improved simply by changing the quantity surveyor's role to one of establishing the cost implications of each option considered. The role should not be one of trying to minimise cost necessarily, but rather establishing which option offers the client the best value for money.

4. There is limited buildability visibility when choosing between design options. Designer's do not have rigorous methods to establish the ease with which a particular option maybe erected.

5. When choosing between options it is more common for designers to use reason drivers which relate to selection on the basis of functional issues. Whilst this is absolutely necessary for the successful design of the building, it is also important for designers to consider options on the basis of process reason drivers. That is, reason drivers such as buildability and their effect on time issues (programme).

6. According to Womack and Jone's (1996) suggestions for lean design (see section 2.2.4), design teams should be multidisciplinary and co-located where possible. The design teams in this study fell short of both these precepts, however, the Gatwick project came closest to achieving it. The BAA framework agreement meant that all of the disciplines were available for consultation from start of feasibility. Although, it must be stressed that simply putting people together, or making them available, does not in itself make a more integrated process. The way in which people interact must be revised to accommodate the early appointment of all the disciplines, production being a prime example. Effective design planning with responsibility allocation can help here.

7. Value engineering could be a useful tool in a lean design environment. Value engineering is used as a means of reducing cost without compromising the functionality of the product.

8. It was found that the most commonly used IT and communication technologies being used to support the design decision making process at the system / sub-system level are the telephone, fax, CAD and word processor. Further consideration should be given to the benefits of three dimensional technologies and document management systems and how they can be integrated into the design process. It is fundamentally important that the process proceeds the technology. A thorough understanding of what the process is trying to achieve is crucial to selecting appropriate technology to support and / or facilitate the process.

9. The study demonstrated a useful way of mapping the design decision making process with the EDGT. These maps can be considered to be value generation

maps as design decisions are the way in which value is added to the product. Value generation maps are a subset of Womack and Jone's (1996) value stream maps. Value generation maps represent the leanest form of design. Design can be considered to be a mixture of value generation – design decisions and design process – the tasks performed to identify and test constraints, devise options and ultimately provide sufficient information to the designer to make an informed decision. Value stream mapping is required to identify waste in the design process. It is important to recognise that there is a difference between the decisions that are made and the tasks which form the decision making process.

The three objectives of this investigation were adequately satisfied. Having identified the potential to make steps towards a standardised approach to the design process, chapter 8 of this thesis will deal with the development of a design decision planning tool based on the findings of this study.

7.16 SUMMARY

This chapter dealt with the mapping of the design decision making process of three live construction projects with an Electronic Data Gathering Tool (EDGT). A number of graphs were produced showing:

- Matched design decisions against normalised time
- Cumulative count of design decisions made against normalised time
- Distribution of design decisions (groups of 0.1 normalised time)
- Distribution of design decisions (groups of 0.05 normalised time)
- Who Made the design decisions
- Percentage of design decisions in which the design team members played an active role
- Percentage of design decisions particular constraint categories as impinging upon the design process
- Percentage of design decisions using particular reason categories to choose between options
- Designer's cost visibility
- The types of meetings where design decisions were made
- Percentage of design decisions using particular information source types
- Percentage of design decisions using particular information technology types
- Percentage of design decisions occurring in each RIBA stage

A number of tables were produced showing:

- List of system / sub-system level design decisions in order of decision occurrence

- List of system / sub-system level design decisions in order of decision maker (defining decision maker roles)
- List of system / sub-system level design decisions that the various disciplines were involved in making (defining decision assistance roles – a table for each discipline)
- List of system / sub-system level design decisions with corresponding constraint and reasons for selection categories
- Information needs

It was found that 73 – 80% of system / sub-system level design decisions are generic in construction projects. These decisions can be made in different orders and at different times during the design process. This information has led to the development of a design planning tool which will help improve control of the design process,, leading towards a more standardised approach to the design process.

The development of a design planning tool called Design Decision Planner (DDP) is documented in chapter 8.

[BLANK PAGE]

CHAPTER 8 TOWARDS LEAN DESIGN: DESIGN DECISION PLANNER (DDP)

"The spirit of a building is in its plan." **Liam Boyd, Director of Stanley Bragg Partnership.**

CHAPTER 8 TOWARDS LEAN DESIGN: DESIGN DECISION PLANNER (DDP) .. 199
8.1 INTRODUCTION 200
8.2 OBJECTIVES 200
8.3 THEORETICAL BASIS 200
8.4 DESIGN DECISION PLANNER (DDP) METHODOLOGY 203
8.5 WORKED EXAMPLE 205
8.6 IMPLEMENTATION 209
8.7 SYSTEMATISATION 210
8.8 CONCLUDING REMARKS 211

8.1 INTRODUCTION

Mapping the design decision making process at the system / sub-system level led to a number of interesting findings. Perhaps the most significant from a lean design perspective is that 73 – 80% of the types of design decisions are generic at the system / sub-system level. These decisions can be made in different orders and at different times during the design process which indicates a considerable degree of flexibility. This knowledge can be used to produce a more detailed design planning method that will move the design process towards a more standardised approach. Having planned design, measuring progress against intended design produces a useful metric.

8.2 OBJECTIVES

The objectives then are to:

1. To create a design decision planning tool that will help to standardise the approach to design and improve control of the design process.
2. The tool should address the order and timing of system / sub-system level design decisions.
3. The tool should address the issue of design responsibility.

8.3 THEORETICAL BASIS

Figure 8.1 shows the cumulative count of decisions made against normalised time for all three case studies investigated in chapter 7. This shows the incidence of system / sub-system design decisions but not what those decisions are. Figures 7.5 – 7.7 attempt to reconcile the actual decisions by matching decisions across pairs of case studies and then plotting them on a normalised time basis. Referring back to figure 8.1, a question can be asked, 'what percentage of the design decisions were completed halfway through the design period?'. Reading vertically upwards from the x-axis to the Bourne curve, say, it can be seen that approximately 60% of the decisions had been made. At 20% of the design period, 7% of decisions, and at 80% design period approximately 92% of design decisions had been made. Taking this real data, the 'target' curve and the 'lower boundary' curve in figure 8.2 were generated. The target curve shows the percentage of the design decisions that the design team should aim to make by a particular point in the design process. The lower boundary indicates the level that the design team should not fall below for a particular point in time. These curves can be used as a means of planning how many of the design decisions should be made during any given period of time. Figure 8.3 shows the distribution of the design decisions to be made against normalised time. This provides an indication of the design effort required over time.

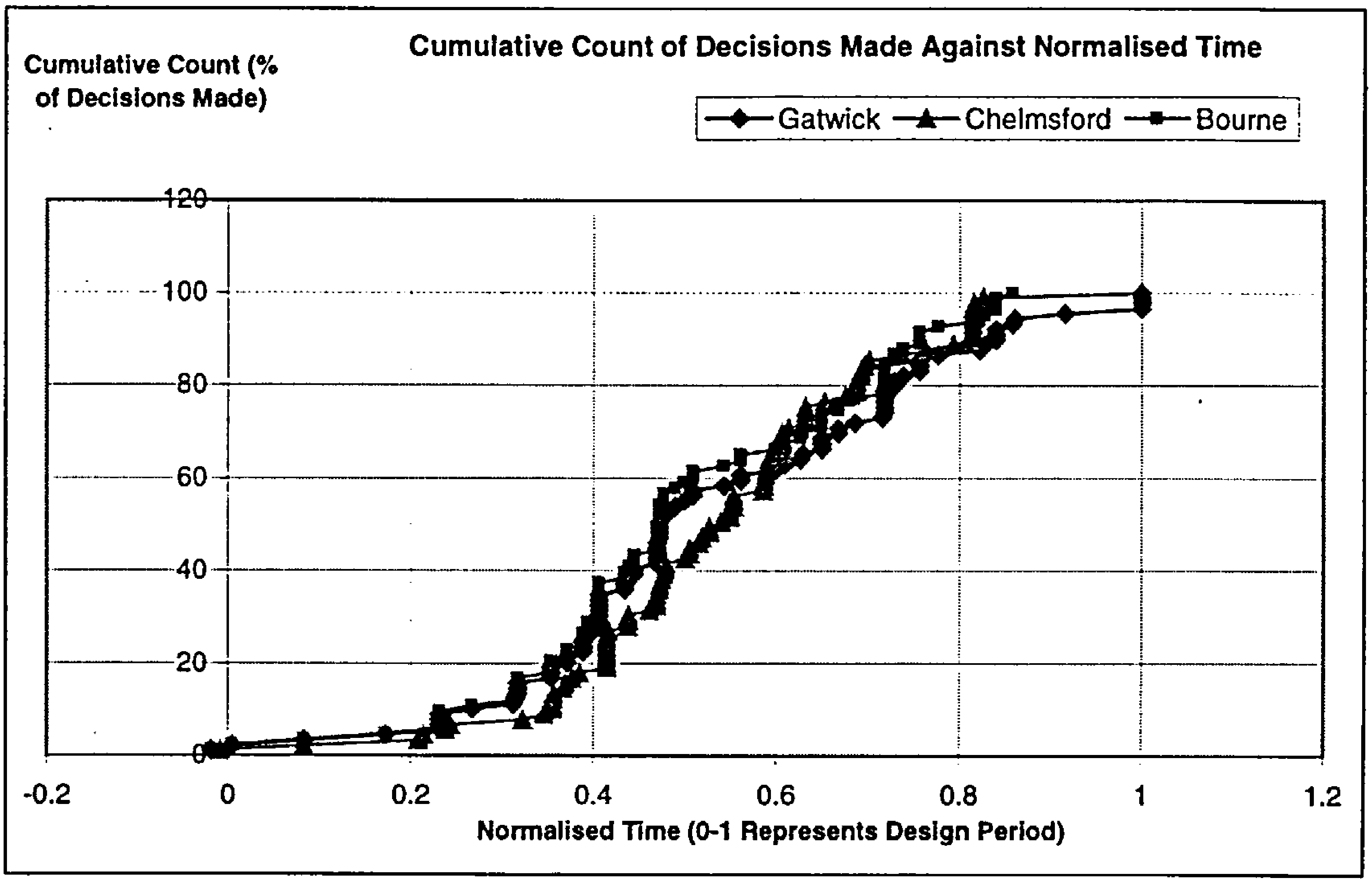


Figure 8.1 – Cumulative Count of Decisions Made Against Normalised Time (all three case studies)

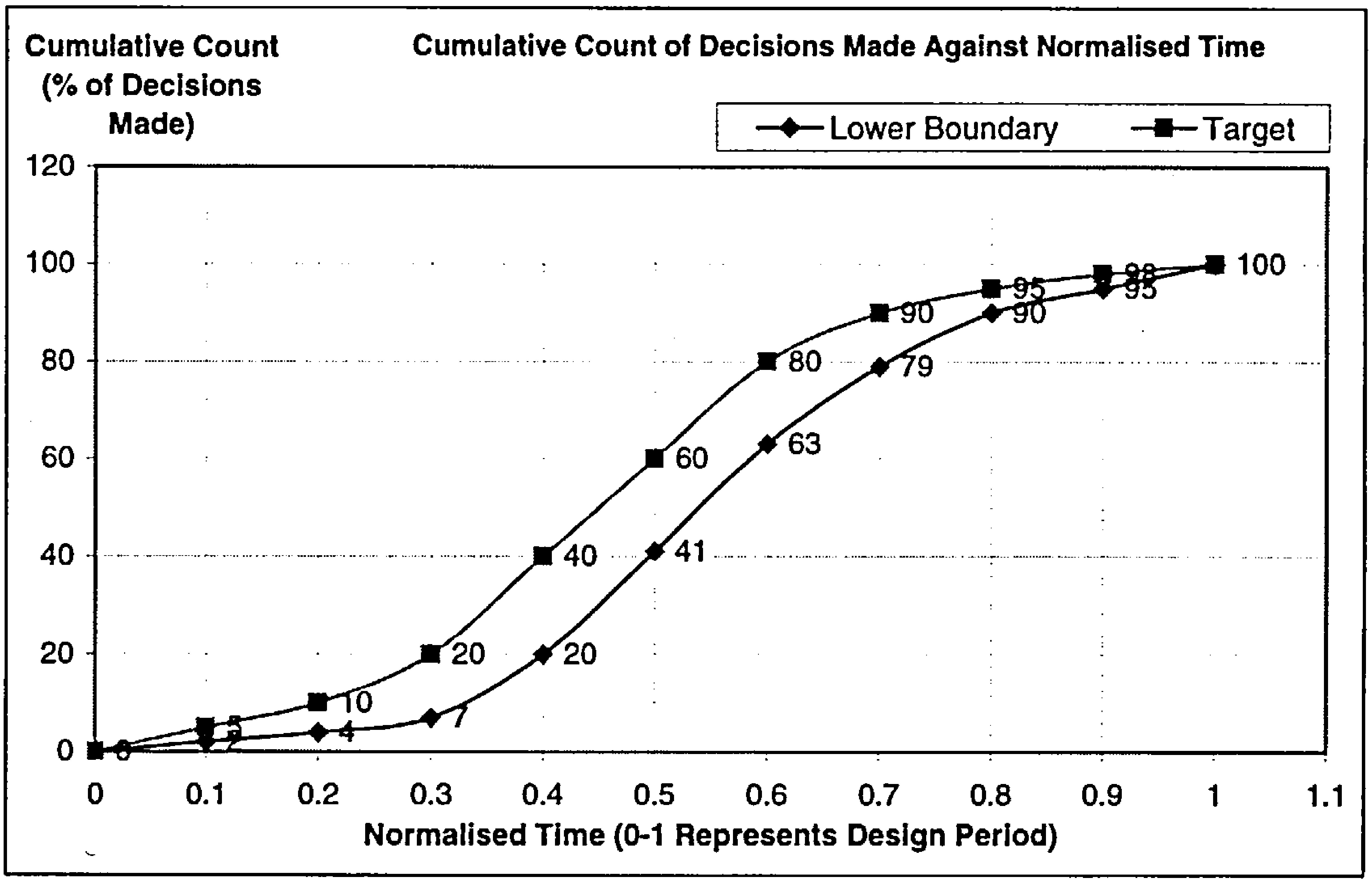


Figure 8.2 – Cumulative Count of Design Decisions to be Made Against Normalised Time

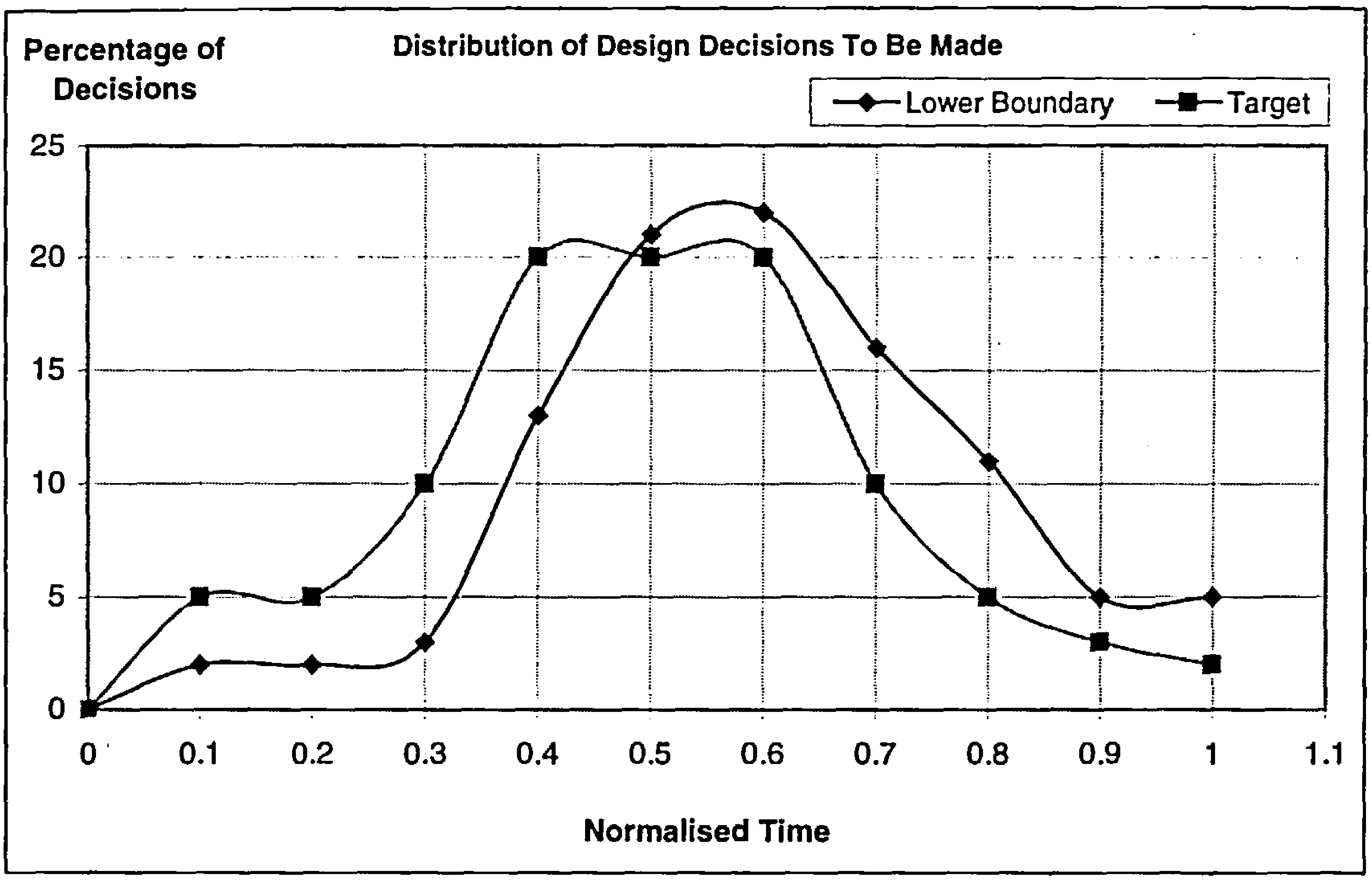


Figure 8.3 – Distribution of Design Decisions to be Made Against Normalised Time

Normalised Time Period	The cumulative 'target' percentage of design decisions to be completed	The cumulative 'lower boundary' percentage of design decisions to be completed
0.1	5 [5]	2 [2]
0.2	10 [5]	4 [2]
0.3	20 [10]	7 [3]
0.4	40 [20]	20 [13]
0.5	60 [20]	41 [21]
0.6	80 [20]	63 [22]
0.7	90 [10]	79 [16]
0.8	95 [5]	90 [11]
0.9	98 [3]	95 [5]
1.0	100 [2]	100 [5]

Table 8.1 – Cumulative 'Target' and 'Lower Boundary' Percentages of Design Decisions to be Completed Over Normalised Time

Table 8.1 shows the cumulative 'target' and 'lower boundary' percentages of design decisions to be completed over normalised time, with the percentage of design decisions to be made in each time period in square brackets. The values are taken from figures 8.2 and 8.3.

To make use of the curves produced in figure 8.2 the design team needs to identify all the system / sub-system level decisions which need to be made for the project. This can be achieved with a mixture of the design team's experience and the lists of decisions accumulated in the value generation maps (see chapter 7). It is the value generation maps which makes design planning at this level of detail a realistic proposition for a professional design team, as the effort required to do this for each project would most likely be deemed unacceptable without them. The list of design decisions for each case study can be found in appendices G, H and I. The design team can select from the lists those decisions which are pertinent to the project, omit those which are not, and produce a new list of any decisions specific to the project. One further piece of information is required before planning can begin and that is the client's desired completion date.

8.4 DESIGN DECISION PLANNER (DDP) METHODOLOGY

The following are the steps necessary for planning design decisions:

1. Identify the list of system / sub-system level design decisions that have to be made for the project. The design planners can use the lists of decisions in appendices G, H and I as a basis for this task. Other project specific design decisions should also be included.

2. The design period should then be calculated. The dates will be specified on the basis of the client's desired programme. Working backwards from the anticipated project completion date an estimation can be made of when the design period will start and end. The start of the design period is defined as the inception of the project, and the end the of the design period is the anticipated date that the contract is to be placed. To calculate normalised time, the inception is taken as zero and the end of the design period as 1. A fraction or decimal between 0 and 1 represents every other date in between.

3. Order the list of decisions in the manner that is best suited for the particular project. This can be done on experiential basis or using more formal methods such as Design Structure Matrix (DSM) (see section 2.5.3.3). Whichever method is used careful attention should be given to the interdependencies between decisions. It should also be remembered that the design team will use this plan to order their work over the design period. This could help value to 'flow' through the process.

4. Having ordered the decisions, reference should be made to table 8.1 (or figure 8.2) 'target' curve, to see how many design decisions should be completed by a particular point in time - Count the number of decisions in the list and then work out 5%, 10%, 20%, 40%, 60%, 80%, 95% and 98% of that number. These percentages represent the cumulative amount of the design decisions which need to be completed by the 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% stage of the design period, respectively. The order of the decisions will determine which normalised time period a particular decision will fall into.

5. Each decision should be assigned a 'to be made by date'. This can be done coarsely in that every decision that falls into a 10% normalised time period has

to be completed by the end of that period, or in a more refined fashion by giving each decision an individual date within a particular 10% time period.

6. The responsibility for each design decision should be allocated to a particular discipline. This should help reduce any ambiguity about who is responsible for a particular issue.

7. Produce a table of design decisions which is then given to each design team member. The table should have the following headings:

Decision Number / Code	Decision Description	Decision to be made by date (normalised time)	Decision to be made by date (calendar date)	Person responsible for design decision	Completed on time

Each 10% normalised time period should be clearly marked to make the table easy to read.

8. Continuous monitoring of progress against planned design should be carried out. If progress does not match planned design, efforts should be made to identify the reasons why. This can then be fed back to the design team / lead consultant who can then make the appropriate corrective action. It also provides an opportunity for the design team to learn from their mistakes to improve performance.

9. A review of the entire planning process versus the way the design team performed should be assessed to find ways of improving design planning and design performance.

Associated with each design decision in the case studies in chapter 6 was information identifying, not only the person who made the decision, but also the other people who were consulted or made a significant contribution to the decision making process. On the basis of this information, checklists could be drawn up for each decision of the people who the decision makers have to consult before making the final decision. This could also form the basis for an approval system, in that the lead consultant will not accept that a particular decision has been made until all the appropriate people have made their inputs. This list would also include specialist consultants and could lead to consideration about which decisions will be particularly sensitive to the local planning authority. This would take a step closer to Latham's (1994) desire for design checklists. Similar lists could be drawn up for information sources to be consulted and IT tools to be used.

This approach to planning and controlling the design process has been called Design Decision Planner (DDP).

8.5 WORKED EXAMPLE

The first step to planning at the design decision level is to identify the system / sub-system levels to that need to be made. For the purposes of this example, data recorded for the Bourne case study in chapter 7 will be used. The list of decisions is taken from table I.1 in appendix I. Decisions are normally identified using existing lists of decisions such as those in appendices G, H and I, and also by design team experience. The next step is to calculate how many of the design decisions have to be made in each 10% of normalised time period. To do this count the number of decisions that have to be made, 83 in this example, and refer to table 8.1 (or figure 8.2) to establish the distribution of when those decisions need to be made over time. Table 8.2 shows the cumulative number of decisions that need to be completed over time for this example. The numbers in the square brackets represent the number of decisions which have to be made in each normalised time period. The design period should then be calculated by working backwards from the client's desired completion date. In this example a design period of 360 days is assumed starting on the 1st January 1999 (inception) and ending 27th December 1999 (date of placing contract). This means that one day represents 1/360 of normalised time (~ 0.0027777). Table 8.3 shows the normalised time periods and their equivalent calendar dates.

Normalised Time Period	The cumulative 'target' percentage of design decisions to be completed	The cumulative 'target' number of design decisions to be completed
0.1	5 [5]	4 [4]
0.2	10 [5]	8 [4]
0.3	20 [10]	17 [9]
0.4	40 [20]	33 [16]
0.5	60 [20]	50 [17]
0.6	80 [20]	66 [16]
0.7	90 [10]	75 [9]
0.8	95 [5]	79 [4]
0.9	98 [3]	81 [2]
1.0	100 [2]	83 [2]

Table 8.2 – Worked Example: The Number of Decisions That Need To Be Completed Over Time

Normalised Time Period	Cumulative Number of Days	End of Period Calendar Date
0.0	0	1st January 1999
0.1	36	6th February 1999
0.2	72	14th March 1999
0.3	108	19th April 1999
0.4	144	25th May 1999
0.5	180	30th June 1999
0.6	216	5th August 1999
0.7	252	10th September 1999
0.8	288	16th October 1999
0.9	324	21st November 1999
1.0	360	27th December 1999

Table 8.3 – Normalised Time Periods and Their Equivalent Calendar Dates

The design decisions then have to be ordered in the manner that best suits the particular project. For this example the order in which the decisions were made in the Bourne project has been retained. This can be done by hand, based on the experience of the design team, or by using more formal methods such as DSM (see section 2.5.3.3). The decisions then need to be broken down into normalised design periods based on the figures calculated in table 8.2. This provides an appropriate distribution of design decision making over time. Individual decisions can then be assigned dates for when they have to be completed within the boundaries of a particular design period (see table 8.4). For the purposes of this example each decision was uniformly spread throughout the design period. For example, a 10% design period represents 36 days. Taking 0 – 0.1 normalised time, 4 decisions have to be made which means that the first will be made 9 days after inception, the second 18 days after inception, the third 27 days, and so on. This assumes an equal amount of design effort is required for each of the decisions. Experienced designers should be able to modify the dates to account for the variation in design effort required.

The responsibility for each decision should then be assigned to particular disciplines. The disciplines shown in table 8.4 are the people who actually made the decisions in the Bourne case study. It is important that all disciplines are made aware of the design plan and agree the assigned responsibilities. Progress should be monitored against planned design, with any deviation from the plan being highlighted and discussed. Any modifications to the plan should be distributed to the rest of the design team.

Decision Number	Bourne Design Decision Made	Decision Maker	Normalised Time Period	Completion Date (Normalised)	Completion Date (Calendar)
1	Extent of demolition on site - buildings at ground level	Architect	0.1	0.025	10-Jan-99
2	Extent of the ground level demolition	Developer	0.1	0.05	19-Jan-99
3	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)	Highways Engineer	0.1	0.075	28-Jan-99
4	Structural bay / grid dimensions	Architect	0.1	0.1	06-Feb-99
5	Footprint of initial building design	Architect	0.2	0.125	15-Feb-99
6	Selection of the frame system / material	Architect	0.2	0.15	24-Feb-99
7	Customer & staff car parking surface material selection	Developer	0.2	0.175	05-Mar-99
8	Landscaping approach (decision for 30k budget)	Architect	0.2	0.2	14-Mar-99
9	Selection of lift system for loading bay	Developer	0.3	0.211111111	18-Mar-99
10	Selection of the roof system / material	Developer	0.3	0.222222222	22-Mar-99
11	Selection of internal skin material	Developer	0.3	0.233333333	26-Mar-99
12	Arrangement of the roof structure	Developer	0.3	0.244444444	30-Mar-99
13	Selection of the roof structure type	Developer	0.3	0.255555556	03-Apr-99
14	Arrangement of the roof system / profile	Developer	0.3	0.266666667	07-Apr-99
15	Selection of external skin system / material	Developer	0.3	0.277777778	11-Apr-99
16	Type of fire compartmentation to be used (partition wall - between sales and domestic)	Developer	0.3	0.288888889	15-Apr-99
17	Type of internal partition wall used (to define areas of space for different uses)	Developer	0.3	0.3	19-Apr-99
18	Surface finish of service yard	Structural Engineer	0.4	0.30625	21-Apr-99
19	Position of service bays	Client - Sainsbury	0.4	0.3125	23-Apr-99
20	Specifying the amount of glazing required	Architect	0.4	0.31875	25-Apr-99
21	CCTV (internally only)	Client - Sainsbury	0.4	0.325	28-Apr-99
22	Telecommunications specification (telephones, computer lines, Granada satellite system)	Client - Sainsbury	0.4	0.33125	30-Apr-99
23	Customer & staff car parking location	Architect	0.4	0.3375	02-May-99
24	Selection of substructure system / material	Structural Engineer	0.4	0.34375	04-May-99
25	Selection of the floor system / configuration	Structural Engineer	0.4	0.35	07-May-99
26	Selection floor finish (concrete floor finish - not final finish)	Contractor	0.4	0.35625	09-May-99
27	Configuration / Layout of the structure	Architect	0.4	0.3625	11-May-99
28	Positioning the service meter cupboard	Services Engineer	0.4	0.36875	13-May-99
29	Extent of the below ground level demolition	Structural Engineer	0.4	0.375	16-May-99
30	Decision to have an acoustic screen around exposed plant	Architect	0.4	0.38125	18-May-99
31	Location of plant room	Client - Sainsbury	0.4	0.3875	20-May-99
32	Configuration of ventilation system	Services Engineer	0.4	0.39375	22-May-99
33	Location of the substation	Services Engineer	0.4	0.4	25-May-99
34	Type of ventilation system selected	Services Engineer	0.5	0.405882353	27-May-99
35	Rendered panel in external skin	Architect	0.5	0.411764706	29-May-99

36	The organisation of internal space	Client - Sainsbury	0.5	0.417647059	31-May-99
37	Decision to have open / closed plant	Client - Sainsbury	0.5	0.423529412	02-Jun-99
38	Location of service yard	Client - Sainsbury	0.5	0.429411765	04-Jun-99
39	Location of the lift system	Client - Sainsbury	0.5	0.435294118	06-Jun-99
40	Type of fire compartmentation to be used (partition wall - between sales and domestic)	Fitout Architect	0.5	0.441176471	08-Jun-99
41	Decided to include a pedestrian walkway canopy	Architect	0.5	0.447058824	10-Jun-99
42	Selection of the roof system / material for the plant room	Contractor	0.5	0.452941176	13-Jun-99
43	Arrangement of external skin - depth of wall (size of cavity)	Architect	0.5	0.458823529	15-Jun-99
44	Selection of Insulation type	Architect	0.5	0.464705882	17-Jun-99
45	Gas capacity	Services Engineer	0.5	0.470588235	19-Jun-99
46	Routing of water supply (decided to route with other services)	Services Engineer	0.5	0.476470588	21-Jun-99
47	Water capacity	Services Engineer	0.5	0.482352941	23-Jun-99
48	Routing of gas supply (decided to route with other services)	Services Engineer	0.5	0.488235294	25-Jun-99
49	Selection of insulation material for the roof	Contractor	0.5	0.494117647	27-Jun-99
50	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure	Client - Sainsbury	0.5	0.5	30-Jun-99
51	Dimension between external skin and gridline	Contractor	0.6	0.50625	02-Jul-99
52	Specification of the building footprint / configuration	Architect	0.6	0.5125	04-Jul-99
53	Final footprint for building design	Client - Sainsbury	0.6	0.51875	06-Jul-99
54	Paving material selection	Architect	0.6	0.525	09-Jul-99
55	Selection of car parking lighting system	Architect	0.6	0.53125	11-Jul-99
56	External signage configuration	Client - Sainsbury	0.6	0.5375	13-Jul-99
57	External skin - architectural features	Architect	0.6	0.54375	15-Jul-99
58	Selection of material for external skin	Architect	0.6	0.55	18-Jul-99
59	To include wind catchers in the roof system	Client - Sainsbury	0.6	0.55625	20-Jul-99
60	Specification of internal doors	Fitout Architect	0.6	0.5625	22-Jul-99
61	Selection of the final floor finish	Fitout Architect	0.6	0.56875	24-Jul-99
62	Cut and fill exercise required to level off the site (store level on site)	Contractor	0.6	0.575	27-Jul-99
63	Bracing to steel frame (amount and arrangement)	Structural Engineer	0.6	0.58125	29-Jul-99
64	Escape routes defined	Fitout Architect	0.6	0.5875	31-Jul-99
65	Fire protection for structural steel	Fitout Architect	0.6	0.59375	02-Aug-99
66	Fire compartmentation	Fitout Architect	0.6	0.6	05-Aug-99
67	Routing of electrical services	Services Engineer	0.7	0.611111111	09-Aug-99

68	Specification of public access doors	Fitout Architect	0.7	0.622222222	13-Aug-99
69	Routing of soiled water drain (roof and landscape water run off)	Structural Engineer	0.7	0.633333333	17-Aug-99
70	Capacity of soiled water drain (roof and landscape water run off)	Structural Engineer	0.7	0.644444444	21-Aug-99
71	Capacity of foul water drain	Structural Engineer	0.7	0.655555556	25-Aug-99
72	Routing of foul water drain	Structural Engineer	0.7	0.666666667	29-Aug-99
73	Selection of roof drainage system	Contractor	0.7	0.677777778	02-Sep-99
74	The decision to include recycling facilities on the service road - i.e. to service yard	Client - Sainsbury	0.7	0.688888889	06-Sep-99
75	Decision to incorporate a gas permeable membrane into the substructure	Structural Engineer	0.7	0.7	10-Sep-99
76	Car park drainage system	Architect	0.8	0.725	19-Sep-99
77	Specification of means of escape doors	Architect	0.8	0.75	28-Sep-99
78	Specification of service doors	Architect	0.8	0.775	07-Oct-99
79	Selection of store perimeter lighting	Services Engineer	0.8	0.8	16-Oct-99
80	Selection of the type of windows / glazing	Architect	0.9	0.85	03-Nov-99
81	Specification of service yard gate	Architect	0.9	0.9	21-Nov-99
82	Enclosure type for substation	Architect	1	0.95	09-Dec-99
83	Capacity of the substation	Developer's QS	1	1	27-Dec-99

Table 8.4 – Worked Example: List of System / Sub-System Level Design Decisions by Split into Appropriate Normalised Time Periods

8.6 IMPLEMENTATION

The implementation of Design Decision Planner (DDP) will largely be dependent upon how a particular project has been initiated. In an ideal world all design specialists would be known at the start of the project and, even if not actively involved in the design, would be available for consultation. In this situation the design team should gather together and discuss the planning of the design process in a dedicated meeting. The team should discuss the best order for the decisions to be made in, identify any project specific decisions and assign appropriate responsibilities to those most competent to deal with them. Discussion could also include refining the 'dates that decisions have to be made by'. However, in most situations the whole design team is unlikely to be known from the outset. At inception, perhaps only the client and architect will be involved, as in the cases of Chelmsford and Bourne. In this situation the tool should be used to cover just those aspects of design (particular decisions) that the client wishes the designer to consider, with all responsibility assigned to the single discipline. The tool should be used again to refine the original plan as other disciplines come on board and / or the scope of the project changes.

The tool is most likely to be used by the lead consultant on a project. It should be the responsibility of a single individual whether the lead consultant or somebody nominated by the lead consultant. For the purposes of this thesis this person will be known as the 'design planner'. It is vital that the design planner makes sure that everybody is aware of the decisions that have been assigned to each discipline and that they are happy with the timing of those decisions. Every discipline should be given a copy of the plan to work from. Any modifications to the plan should be made through the design planner who can then issue an updated version, ensuring that everybody concerned is made aware of the changes that have been made. It may be that a graphical version of the tool can be developed to aid in the visualisation of design planning. Alternatively, the tool could be translated into a Gantt chart with the decision milestones clearly visible. Design progress should be assessed at each design team meeting. Any deviation from the plan should be reported and the reasons why divulged to the team. This allows the design team to take corrective action on issues arising. It also allows the design planner to make any modifications required to the design plan.

8.7 SYSTEMATISATION

DDP could be systematised into a computer programme. This ultimately must be the aim of the design planning approach to assist both design control and planning transparency. Through systematisation, a read only version of the plan could be located on a project website / network that every design team member could gain access to. Systematisation could also help with the idea of an approvals system which requires confirmation of inputs from various disciplines for each decision. Not only could check lists of people be included but also of particular pieces of information that have to be found or tools that have to be used. Associated with each of these pieces of information there could be a number of hyperlinks that direct designers to online resources such as the appropriate design standards, building regulations, etc. As a decision is finalised there could be a simple calculation performed that automatically charts the progress of the design team. The tool could also be used to flag up decisions which have not been made yet but are approaching the 'to be completed by dates'. A different indicator could be used for those decisions which have not been made and have exceeded their 'to be completed by dates'. Both of these indicators should stimulate the design team to deal with those particular design decisions. With an appropriate Graphical User Interface (GUI) a systematised version of DDP could provide a more user friendly approach to design planning and aid in the visualisation of the plan. Systematisation would also help facilitate modifications to the plan and reusability for the next project. A number of lists of decisions could be stored which could be used as templates for certain types of project. The design team / planner would then only have to consider how each project deviated from the appropriate template because of its unique characteristics. If there was sufficient divergence from all available templates, that project could serve as a template for future projects.

8.8 CONCLUDING REMARKS

A tool has been presented which aids design planning at the system / sub-system level for construction projects. Its feasibility lies in the finding that there are over 73% generic design decisions between construction projects. This undermines the commonly held view that each construction project is unique. It is of course unique at the detailed level, however, it is the types of decisions that have to be made that are common across projects. The tool will be easy to use until there is a paradigm shift in the way buildings are produced. A paradigm shift would require an analysis to identify the new set of decisions that are common to construction projects or, indeed, to see if there is still a generic set of decisions. The tool could still be used without a generic set of decisions, it just means that more effort would be required by the design team at the beginning of each project, which might be deemed unacceptable. The tool is presented in longhand form. It is envisaged that for practical purposes it will be systematised into software to expand its potential and to facilitate some of the ideas expressed in section 8.7. Making use of design decision templates, whether in longhand or systematised form, could help to standardise the approach to construction design. This does not mean to standardise design itself, that is the creative aspects of design, but rather the way in which design is perceived at the project team, or organisation level. This is an important step in creating a lean design environment. Measuring progress against planned design will help to create a stronger culture of project review which is another important component of lean product development (Heilman, 1999).

The development of DDP should help dispel the belief amongst designers that Coles (1990) found that design planning is not possible.

The significance of the findings of the entire research project in relation to the objectives of the study are presented in chapter 9.

[BLANK PAGE]

CHAPTER 9 SIGNIFCANCE OF THE RESULTS

"There is no point in asking people to tender who are consistently uncompetitive. People who are coming fifth and sixth on our list every time would not be asked again as they are taking up space from somebody who could be competitive." **Sean Horkan, BAA Lynton plc.**

CHAPTER 9 SIGNIFCANCE OF THE RESULTS 213
9.1 MEETING THE OBJECTIVES 214
9.2 RESEARCH ACHIEVEMENTS / MAIN FINDINGS 216
9.3 THE VALUE OF THIS WORK 219

9.1 MEETING THE OBJECTIVES

A study has been conducted into the application of lean thinking to construction design. The investigation consisted of researching work previously conducted in the field by other researchers to identify the state of the art. The change order request system was examined to gain first insights into waste in construction design and to gauge the size of the opportunity for the application of lean thinking. An Electronic Data Gathering Tool (EDGT) was then developed to allow further exploration of the design decision making process in construction at the system / sub-system level. The EDGT was used on three live construction projects to record data about design decision making. From this data a design planning tool, Design Decision Planner (DDP), was created to help improve control of the design process and lead to a more standardised approach, together with other recommendations to make construction design lean.

The success of this study should be considered with due reference to the objectives of the work. The objectives stated at the beginning of this thesis are as follows:

1. Apply lean thinking principles to construction design.

2. Assess the potential benefits of lean construction design.

3. Make recommendations on becoming 'lean' (for construction design).

9.1.1 The Application of Lean Thinking Principles to Construction Design

The general themes of the work are outlined in the first objective. To ensure that this aim was fulfilled a comprehensive literature survey was conducted into both lean thinking and design to establish the current understanding of both themes (see chapters 2 and 3).

9.1.2 Potential Benefits of Lean Construction Design

The second objective was met in two ways. Firstly, the literature survey identified the types of benefits that the application of lean thinking has led to in manufacturing, and to some extent, construction. From the examples cited, lean thinking reputedly leads to big increases in sales per employee, reduces lead times – both product development and the production of individual articles, reduction in inventories – both in-process and finished goods, less space required and a simplified supply chain. This is through the application of lean thinking throughout the organisation, however, not just one process such as design. The literature is useful in that it is indicative of the types of improvements that can be expected and, indeed, suggestive of the routes that can be taken to achieve some of the benefits of lean thinking. However, further steps were necessary to quantify the potential savings that could be made through the application of lean thinking to construction design specifically. The second approach taken was to identify a waste stream in the design process, calculate the impact that it has on construction projects, and deduce the magnitude of the opportunity to make cost savings by making construction design lean.

The type of waste identified was change orders. It was found that change orders cost between 5.1% and 7.6% of the total project cost for the well managed and successful projects studied. These figures are likely to be an underestimate for typical projects by virtue of the case histories alleged success. Also, the figures are based solely on direct costs to the project and take no account of the impact on productivity, disruption and the programme. It is also important to note that change orders only constitute one type of waste in construction design and that the addition of other waste components will add to the level of inefficiency. It may be, however, that other types of waste do not impact projects in the same order of magnitude. Nevertheless, change orders represent significant sums of money which should be of great concern to construction companies and clients. It was also found that an average of 63%, with a high of 95%, of the cost of change orders were due to process issues, that is, reasons that were in the control of the design team, or that the design team could impact. This suggests that better control of the design process could lead to significant savings and smoother running of the entire construction project.

9.1.3 Recommendations for Construction Design to Become Lean

The following recommendations to make construction design lean, are made on the basis of the findings from the literature survey (chapters 2 and 3), the change order request analysis (chapter 5), mapping the design decision making process at the system / sub-system level (chapter 7) and the development of a design planning tool (chapter 8).

1. It has been observed that there is a deficiency in design planning in construction projects. This observation is corroborated in the literature. This can lead to insufficient information being available to complete design tasks and inconsistencies with construction documents (Formoso et al, 1998). Indeed, the design process needs to be better controlled to reduce the effects of complexity and uncertainty. A method called Design Decision Planner (DDP) has been developed which should lead to increased control of the design process. Design planning is centred on decisions that have to be made to add value to the product. The tool was developed on the basis of the finding that between 73 – 80% of design decisions made at the system / sub-system level are generic across construction projects. The tool uses lists of decisions which were recorded during the data gathering exercise as a starting point to identify the list of decisions that is peculiar to the project under consideration. The entire design team should be involved in design planning with the ultimate responsibility assigned to one individual – the 'design planner'. The order and timing of decisions is specified and the responsibility for individual decisions assigned to appropriate design disciplines. This leads to a more clearly defined and transparent process. It is also envisaged that this will lead to a more standardised approach to construction design.

2. Additional value stream mapping may be appropriate to assess the tasks that need to be performed for each design decision. It may help to identify the information needs of each discipline for any particular decision. It could also help value 'flow' through the design process.

3. When choosing between design options, designers need to concentrate more on process issues such as the difference in lead times, cost of each option and ease of buildability. Most options were found to be selected on the basis of functional criteria. Whilst functional issues are imperative, any design options which meet the technical specification should then be considered largely on the basis of process criteria rather than superior function.

4. Another deficiency observed in construction design was the lack of cost and programme visibility when choosing between options at the time of making the decisions. This needs to be addressed. One way of tackling the issue could be to redefine the role of the quantity surveyor from cost controller to a more integrated role of 'value for money assessor'. The assessor would work more closely with the designers, costing each of the design options considered and try to match this with what the client values.

5. The early appointment of the various design professionals would mean that there is a larger pool of expertise to draw upon from the outset of the project. Co-locating the team would also lead to greater synergy between disciplines and reduce the problems associated with information transactions. Co-location of teams for construction projects may not always be possible especially when designers are working on other projects. In this situation the use of appropriate IT may help ease the problem. A caveat to this issue is that the 'design process', or the interaction between designers, must be the primary issue when selecting / devising IT tools to support design activity.

6. It was also apparent that there is a lack of formal methods for rigorously assessing the buildability of design options. This suggests that buildability is also a blind spot for designers. This should be the subject of further research, however, in the short-term, the early appointment, or designation, of construction professionals may help ease this issue.

7. The change order request system could be redesigned with process improvement in mind. Any system employed should seek to establish the root causes of change orders as well as offering traceability for contract issue design changes. The data produced by the system should be analysed regularly to flag up problem work packages during a project, and process deficiencies in a post project review.

9.2 RESEARCH ACHIEVEMENTS / MAIN FINDINGS

The following is a brief summary of the main findings from chapters 5, 6, 7 and 8 of this thesis.

9.2.1 From the Change Order Request Analysis (Chapter 5)

1. Change orders constitute waste in construction design and are symptomatic of problems occurring within the design process. The data studied does not specifically identify what the problems are but rather points an 'accusatory finger' towards process issues in the early decision making process.

2. Change orders cost between 5.1% and 7.6% of the total project cost for the well managed and successful projects studied. These figures are likely to be an underestimate for typical projects by virtue of the case histories alleged success.

3. It was found that an average of 63% (with a high of 95%) of the cost of change orders related to process issues, on the basis of the projects studied.

4. A means of showing the cumulative affects of change orders on a construction project has been demonstrated. The technique considers the incidence of change orders and cost build up on a work package basis over a normalised time axis. This approach facilitates comparisons of dissimilar work packages within a project, and similar work packages across projects.

5. It was found that the change order request process was aimed primarily at handling the contractual implications of late design changes rather than a process improvement tool.

6. The change order request system could be modified to incorporate a process improvement philosophy, whilst containing sufficient elements of the existing system to control the modification of contract issue design changes.

9.2.2 Developing the Electronic Data Gathering Tool (EDGT) (Chapter 6)

1. A data gathering tool was designed and systematised in Microsoft Access 97™ to map the design decision making process in construction projects.

2. The data recorded can be split into three broad areas: decision factors, process factors and administrative issues. The decision factors are those which relate directly to the decision, such as specifying decision, constraints, options and reasons for selecting / rejecting options. Process factors are those which relate to how the decision was made: who made the decision, who else was involved, what IT tools and information sources were used to help support the decision making process. Administrative issues are to do with identification of data to help at the analysis stage.

3. The data collected facilitates the comparison of construction projects and allows a generic set of decisions to be identified. These decisions can be compared on the basis of time to see whether they were made in the same or similar order, and made at about the same time during the design period.

4. The EDGT could be adapted and used as a QA tool.

9.2.3 From the Mapping of the Design Decision Making Process (Chapter 7)

1. There is 73 – 80% design decision commonality across projects at the system / sub-system level. These decisions were made in different orders and at different times during the design process. This means that the timing and ordering of decisions is variable.

2. There is limited cost and programme visibility when choosing between design options when making a particular design decision. That is the designer is not able to assess the cost and programme impact of selecting one option over another.

3. Related to finding number two is the role of the quantity surveyor within the project. The current role is one of cost control rather than active participation within design process. Cost visibility maybe improved simply by changing the quantity surveyor's role to one of establishing the cost implications of each option considered.

4. There is limited buildability visibility when choosing between design options.

5. When choosing between options it is more common for designers to use reason drivers which relate to selection on the basis of functional issues rather than process issues.

6. It was found that the most commonly used IT and communication technologies being used to support the design decision making process at the system / sub-system level are the telephone, fax, CAD and word processor.

7. The study demonstrated a useful way of mapping the design decision making process with the EDGT. These maps can be considered to be value generation maps as design decisions are the way in which value is added to the product. Value generation maps are a subset of Womack and Jone's (1996) value stream maps.

9.2.4 Developing Design Decision Planner (DDP) (Chapter 8)

1. A design planning tool has been developed for system / sub-system level design decisions. This tool has been called Design Decision Planner (DDP).

2. Its usefulness lies in the finding that 73 – 80% of the types of design decisions at this level are generic across construction projects.

3. The incidence of design decision making follows a standard 'S' curve when plotted against a normalised time axis regardless of the composition of the design team or contractual arrangement.

4. The distribution of the timing of decisions has been identified. DDP indicates the number of decisions that should be made within each 10% normalised time period.

5. The timing of individual decisions within 10% normalised time periods can be specified.

6. The ordering of design decisions is variable and can be tailored to each project. This can be achieved through design team experience and / or formal methods such as Design Structure Matrix (DSM).

7. The responsibility for particular decisions is assigned to specific design team members.

8. DDP can be systematised to increase its functionality and accessibility. It could also be used to incorporate an approvals system.

9. DDP can be used to improve control and visibility of the design decision making process.

10. DDP could lead to a more standardised approach to construction design which is an important component of lean product development.

11. Measuring progress against planned design is a useful process metric.

9.3 THE VALUE OF THIS WORK

The value of this work can be split into two categories: the immediate benefits to the construction industry and the contribution to the deposit of knowledge which, in the long-term, may help to shape future research. The immediate benefits to the industry lie in the adoption of some or all of the recommendations for making construction design lean. In particular, making use of DDP to plan and control the design process. The tool will help to define design responsibilities, the timing and ordering of decisions and also to make the process more transparent. DDP will also help to make the approach to construction design more standardised. Ultimately, the real value of DDP will be defined by how useful the tool is to the construction industry, and how widely it is adopted. The problem here often lies with the willingness of designers to try a new approach rather than 'do things the way they have always been done'. As the tool has only recently been created it has not yet been tried on any construction projects and, as such, the usefulness can only be measured against people's initial impression:

"The concept of such a guide is most welcome and should be a useful tool for the industry." Deborah Lazarus, Associate Director, Ove Arup & Partners Research & Development.

"It is a good idea and will get better the more it is used and as data bases [of design decisions and related data] improve." Huw Thomas, Sir Norman Foster & Partners.

"Very novel approach to design management and must be worth publishing in a journal." Stuart Alexander, WSP Consulting Engineers.

"The guide could be useful if used on day one of the design process...The effectiveness of the guide, together with its usefulness, will only become apparent in practice if a change in the culture of the design process is made to accept such a guide." Peter Mullen, Taylor Woodrow Construction, Engineering Division.

The construction industry could also respond to the recommendation that more emphasis be placed upon process issues when making choices between design options. That is, how the design decision will impact other down stream processes. It might also be possible, in the short-term, to address the issue of making construction expertise available in the early design stages. A key issue for the industry in responding to this, and similar work, is for them to change their view of design from a process of conversion to one where waste does exist. Huovila et als' (1994) view of design as conversion, flow and value generation could help in this issue. It is, however, crucially important to realise the significance of design and its effect on other phases of the construction project.

With regard to the deposit of knowledge, a summary of the findings of this work has been outlined in this chapter. Recommendations for further work have been made on the basis of these findings, and are detailed in chapter 10.

CHAPTER 10RECOMMEDATIONS FOR FURTHER WORK

"We'll have to wear different shoes, I'm sure. Plenty of people are trying to put networks into carpets to make buildings more productive and better used." **Huw Thomas, Sir Norman Foster and Partners (on the future of buildings).**

CHAPTER 10 RECOMMEDATIONS FOR FURTHER WORK.................................... 221
10.1 FURTHER STEPS ON THE ROAD TO LEAN DESIGN.................................... 222

10.1 FURTHER STEPS ON THE ROAD TO LEAN DESIGN

The voice of the customer is a crucial aspect of lean product development. It was anticipated when developing the EDGT that it would be possible to investigate the voice of the customer (client's needs) by studying the incidence of the identification of functional requirements by designers, but due to limitations of resources, it was only possible to focus on design decision making. It was hoped that it would be possible to make links between the designer's ability to identify functional requirements and the subsequent decision making process which takes place. To some extent this has already been investigated through research related to QFD (see section 2.5.3.1). However, according to Huovila et al (1995(1)), the tool can be quite difficult and laborious to use. Further research could be conducted into this area looking at the links between identifying functional requirements and design decision making, with the intention of developing more intuitive methods to encapsulate the voice of the client that would be better suited to construction designers.

An interesting discovery from mapping the design decision making process was that construction designers are still largely dependent upon fax, CAD, telephones and word processors to support decision making. It would seem that there is only a partial adoption of three dimensional technologies and use of e-mail and the internet. Further study into the IT and communication technological needs of designers should be conducted. The work should perhaps centre on the designer's needs rather than cutting edge computer technology. That is, it is crucial to understand the process of design to be able to facilitate it effectively. Another issue arising from the process maps is the cost and programme visibility of designers when choosing between design options. It would seem from the study that designers have a very limited ability to assess how each option will impact the project in terms of cost and time. This should certainly be the subject of further study. Related to this is how the quantity surveyor is integrated into the design process. Currently, the role appears to be that of cost controller which does not seem to be the full potential of the position. Research could be undertaken with a view to redefining the role to one of assessing the value for money of each design option produced. This would require the quantity surveyor to work more closely with each design discipline. Another issue related to cost and time visibility is that of buildability. It would also seem that designers have limited means of assessing the buildability of design options. The development of rigorous means of comparing the buildability of options would help support the decision making process. The problem could be eased by considering how construction professionals can be integrated into the early design phases and how the cost / contractual issues can be overcome.

One issue that this work did not address was the interdependencies between design decisions and the corresponding information needs of each design discipline. This is being addressed to some extent, however, by Austin et al (1999). This is a very important issue to ensure the smooth running of design projects. The absence of correct information often leads to design delays. Design delays are a type of waste in the product development process. This study identified change orders as a significant source of waste in construction design, further work should be instigated to establish other types of waste in the design process. The view of design as conversion, flow and value generation (Huovila et al, 1994) may help in this respect. The need for change orders in construction is a significant type of waste because of the consequences that can occur in the production phase. One interesting finding from chapter 5, is that the system used to facilitate late design changes does not collect data with the intention of improving the design decision making process. Research into a new change order request system could be conducted which facilitates contract issue design changes but also seeks out root causes of change orders, with a view to improving design efficiency. A systematised version could be used as a real time project management tool.

Another interesting avenue of research would be to holistically apply the five stage change management approach to construction companies, as advocated by Womack and Jones. It would be interesting to see if the same results that were gained in the manufacturing sector can be achieved by their construction counterparts. It would also be interesting to see what impact this would have on organisation at the project level. Whilst this is of interest from an academic perspective, it would of course be a cause of concern for company directors.

[BLANK PAGE]

REFERENCES

Acharya, P., Pfrommer, C. & Zirbel, C. (1995) 'Think Value Engineering'. Journal of Management in Engineering, November / December, pgs. 13-17.

Agile Construction Initiative (1998) Constructing the Best Government Client: Pilot Benchmarking Study. A report produced by the Agile Construction Initiative, University of Bath, for the HM Treasurary Procurement Group and the Government Construction Panel, October 1998.

Akin, Ö. (1991) A Structure and Function Based Theory for Design Reasoning. Cross, N. (ed) (1991) *Research in Design Thinking - Proceedings of a Workshop held at the Faculty of Industrial Design Engineering,* Delft University of Technology, Netherlands, 29-31 May 1991, pgs. 37-60.

Alarcon, L. (ed) (1997) *Lean Construction.* A.A. Balkema, Netherlands.

Alarcon, L. & Mardones, D.A. (1998) Improving the Design-Construction Interface. *Sixth Annual Conference of the International Group for Lean Construction,* 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Alarcon, L.F., Ashley, D.B. & Teicholz, P. (1997) A Predictive Framework for Decision Making in Construction. *Proceedings of Construction Congress V: Managing Engineered Construction in Global Markets,* pgs. 996-1003.

Alshawi, M. & Underwood, J. (1996) 'Improving Constructability of a Design Solution Through an Integrated System'. International Journal of Engineering, Construction and Architectural Management, vol. 3, no. 1 & 2, pgs. 47-67.

Anderson, S. (1984) 'Architectural Design as a System of Research Programmes'. Design Studies, vol. 5, no. 3, pgs. 147-150.

Anumba, C.J. & Evbuomwan, N.F.O. (1997) 'Concurrent Engineering in Design-Build Projects'. Construction Management and Economics, vol. 15, no. 3, pgs. 271-281.

Anumba, C.J. & Evbuomwan, N.F.O. (1996) A Conceptual Model for Construction Client's Requirements Processing. *Proceedings of the Third Congress of Computing in Civil Engineers,* pgs. 431-437.

Atkin, B. (1998) Unravelling the Value Chain in Construction. *Sixth Annual Conference of the International Group for Lean Construction,* 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Austin, S., Baldwin, A. & Newton, A. (1996) 'A Data Flow Model to Plan and Manage the Building Design Process'. Journal of Engineering Design, vol. 7, no. 1, pgs. 3-25.

Austin, S., Baldwin, A., Li, B. & Waskett, P. (1999) Analytical Design Planning Technique for Programming Building Design. *Proceedings of Institution of Civil Engineers: Engineers, Structures & Buildings,* May 1999, Paper 11783, pgs. 111-118.

Austin, S., Baldwin, A., Baizhan, L. & Waskett, P. (1998) Development of the ADePT Methodology. Department of Civil and Building Engineering, Loughborough University.

Baldwin, A.N., Austin, S., Hassan, T.M. & Thorpe, A. (1999) 'Modelling Information Flow During the Conceptual and Schematic Stages of Building Design'. Construction Management and Economics, vol. 17, pgs. 157-167.

Ballard, G. & Howell, G. (1994) Implementing Lean Construction: Stabilizing Work Flow. *Second Annual Conference of the International Group for Lean Construction,* 28-30 September 1994, Santiago, Chile. Reprinted in Alarcon L. (ed) (1997) *Lean Construction.* A.A. Balkema, Rotterdam.

Ballard, G. & Howell, G. (1998) What Kind of Production is Construction? *Presented at the Sixth Conference of the International Group for Lean Construction,* 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Ballard, G. & Koskela, L. (1998) On the Agenda of Design Management Research. *Sixth Annual Conference of the International Group for Lean Construction,* 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Baya, V. & Leifer, I.J. (1994) 'A Study of the Information Handling Behaviour of Designers During Conceptual Design'. Design Theory and Methodology, vol. 68, pgs. 153-160.

Bishop, D. (1985) Buildability: the Criteria for Assessment. Technical Report: The Chartered Institute of Building, No. 48.

Boothroyd, G. (1994) 'Product Design for Manufacture and Assembly'. Computer - Aided Design, vol. 26, no. 7, pgs. 505-520.

Broughton, T. (1990) Simultaneous Engineering in Aero Gas Turbine Design and Manufacture. *In Proceedings of 1st International Conference on Simultaneous Engineering,* 4-5 December 1990, London, pgs. 25-36.

Browne, J. & O'Sullivan, D. (1995) *Re-engineering the Enterprise.* Chapman & Hall, UK.

Carrara, G., Kalay, Y.E. & Novembri, G. (1992) Computational Framework for Supporting Crateive Architectural Design. Kalay, Y.E. (ed) (1992) *Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 17-35.

Chan, S. (1990) 'Cognitive Processes in Architectural Design Problem Solving'. Design Studies, vol. 11, no. 2, pgs. 60-80.

Chen, S.E., McGeorge, D., Sidwell, A.C. & Francis, V.E. (1996) 'A Performance Framework For Managing Buildability'. *CIB-ASTN-ASO-RILEX The International Symposium: Applications of the Performance Concept in Building,* 9-12 December 1996, Tel Aviv, Israel, pgs. 5:63-72.

Chen, S.E. & McGeorge, D. (1993/4) A Systems Approach to Managing Buildability. Australian Institue of Building Papers, vol. 5, pgs. 75-86.

Clausing, D. & Pugh, S. (1991) Enhanced Quality Function Deployment. *Design and Productivity International Conference,* 6-8 February 1991, Honolulu, Hawaii.

Cleetus, K.J. (1992) Definition of Concurrent Engineering. CERE Technical Report Series, Research Note CERC-TR-RN-92-003, Concurrent Engineering Research Centre, West Virgina University, Morgantown, USA, pgs. 1-5.

Cohen, L. (1995) *Quality function deployment: how to make QFD work for you.* Addison-Wesley, Reading, MA.

Coles, E.J. (June 1990) Design Management: A Study of Practice in the Building Industry. Occasional Paper No. 40, The Chartered Institue of Building.

Construction Industry Institute (CII) (1986) Constructability - A Primer. Publication 3-1, CII, University of Texas, Austin.

Cross, N. (ed) (1992) *Research in Design Thinking.* Delft University Press, Netherlands.

De La Garza, J.M. & Alcantara, P. (1995) Data Structures Supporting Design Rationale Capture. *Computing in Civil Engineering Proceedings of the Second Congress,* ASCE, 5-8 June 1995, Atlanta, Georgia, vol. 2, pgs. 1461-1468.

Deasley, P.J. & Rogerson, J.H. (1997) Best Practice in Construction Management - An Analysis of Modern Manufacturing Concepts. Report from BRE contract EMC 97-32: A Radical Redesign of the In-situ Concrete Frame Process.

Demirkan, H. (1998) 'Integration of Reasoning Systems in Architectural Modeling Activities'. Automation in Construction, vol. 7, no. 2/3, pgs. 229-236.

Ehrlenspiel, K. & Dylla, N. (1993) 'Experimental Investigation of Designers' Thinking Methods and Design'. Journal of Engineering Design, vol. 4, no. 3, pgs. 201-212.

Fisher, N. (1993) Construction as a Manufacturing Process. An Inaugural Lecture, 18 May 1993, Reading University.

Fowler, C. & Gray, C. (1997) Constructional steelwork: a strategy for change by 2005. *Fifth Annual Conference of the International Group for Lean Construction*, 1997, Gold Coast, Australia. http://www.vtt.fi/rte/lean/ (September 1999).

Formoso, C.T., Bernardes, M. & Oliveria L.F. (1998) Developing A Model for Planning and Controlling Production in Small Sized Building Firms. *Sixth Annual Conference of the International Group for Lean Construction*, 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Frankenberger, E. & Badke-Schaub, P. (1998) 'Modelling Design Processes in Industry - Empirical Investigations of Design Work in Practice'. Automation in Construction, vol. 7, no. 2/3, pgs. 139-155.

Fryer, B. (1997) *The Practice of Construction Management.* Third Edition. Blackwell Science Ltd, Oxford.

Gann, D.M. (1996) 'Construction as a Manufacturing Process? Similarities and Differences Between Industrialised Housing and Car Production in Japan'. Construction Management and Economics, vol. 14, no. 5, pgs. 437-450.

Glavinich, T.E. (June 1995) 'Improving Constructability During the Design Phase'. Journal of Architectural Engineering, vol. 1, no. 2, pgs. 73-76.

Goldschmidt, G. (1990) 'Linkography: Assessing Design Productivity'. *Proceedings of Tenth European Meeting on Cybernetics and Systems Research*, 1990, Vienna, pgs. 291-298.

Goldschmidt, G. (1992) Criteria for Design Evaluation: A Process Oriented Paradigm. Kalay, Y.E. (ed) (1992) *Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 67-78.

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

Green, S. (1989) Why Value Management is Different to Value Engineering. MSc Project Management - Reading University, Lecture Notes, October 1989.

Green, S. (1994) 'Beyond Value Engineering: SMART Value Management for Building Projects'. International Journal of Project Management, vol. 12, no. 1, pgs. 49-56.

Hamel, R., (1994) 'A Model of the Architectural Design Process, and Some Implications'. Tzonis, A. & White, I. (eds) (1994*) Automation Based Creative Design.* Elsevier Science, pgs. 334-347.

Hammer, M. & Stanton, A. (1995) *The Reengineering Revolution: The Handbook.* Harper Collins Publishers, UK.

Heilman, G. (1999) *Presentation to Lean Summit 1999.* http://www.lean.org/community/presentations/summit99/Session4G.ppt (August 1999).

Huovila, P., Koskela, L. & Lautanala, M. (1994) Fast or Concurrent: The Art of Getting Construction Improved. *Presented at The Second Conference on Lean Construction*, 1994, Santiago, Chile. Reprinted in Alarcon, L. (1997) *Lean Construction.* A.A. Balkema, Rotterdam.

Huovila, P., Lakka, A., Laurikka, P. & Vainio, M. (1995(1)) Involvement of Customer Requirements in Building Design. *Third Annual Conference of the International Group for Lean Construction,* 16-19 October 1995, Albuquerque, New Mexico. Reprinted in Alarcon, L. (1997) *Lean Construction.* A.A. Balkema, Rotterdam.

Huovila, P., Koskela, L., Lautanala, M., Pietilainen, K. & Tanhuanpaa, V.P. (1995(2)) Use of the Design Structure Matrix in Construction. *Third Annual Conference of the International Group for Lean Construction,* 16-19 October 1995, Albuquerque, New Mexico. Reprinted in Alarcon, L. (1997) *Lean Construction.* A.A. Balkema, Rotterdam.

Isatto, E.L. & Formoso C.T. (1998) Design and Production Interface in Lean Production: A Performance Improvement Criteria Proposition. *Sixth Annual Conference of the International Group for Lean Construction,* 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Johnson, R.E. (1992) Design Inquiry and Resource Allocation. Published in Kalay, Y.E. (ed) (1992) *Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs 50-65.

Kagioglou, M., Aouad, G., Cooper, R. & Hinks, J. (1998) The Process Protocol: Process and IT Modelling for the UK Construction Industry. *Procds. of ECPPM 98 - The Second European Conference on Product and Process Modelling in the Building Industry,* 19-21 October 1998. Amor, R. (ed*) Product and Process Modelling in the Building Industry.*

Kalay, Y.E., Khemlani, L. & Choi, J.W. (1998) 'An Integrated Model to Support Distributed Collaborative Design of Buildings'. Automation in Construction, vol. 7, no. 2,3, pgs. 177-188.

Kelly, J. & Male, S. (1993) *Value Management in Design and Construction - The Econmic Management of Projects.* E & FN Spon, UK.

Kettinger, W.J., Teng, J.T.C. & Guha, S. (1997) 'MISQ Archivist for Business Process Change: A Study of Methodologies, Techniques and Tools'. MIS Quarterly, vol. 21, no. 1, pgs. 55-79.

Kochan, A. (1991) 'Boothroyd / Dewhirst - Quantify Your Designs'. Assembly Automation, vol. 11, no. 3, pgs. 12-14.

Koskela, L., Ballard, G. & Tanhuanpaa, V.P. (1997) Towards Lean Design Management. *Presented at the Fifth Conference of the International Group for Lean Construction,* 1997, Gold Coast Austraila. http://www.vtt.fi/rte/lean/ (September 1999).

Krone, S.J. (1993) Containing Construction Change with Computers. *Proceedings of 5th International Conference - Computing in Civil and Building Engineering*, pgs. 1762-1769.

Latham, M. (1994) Constructing the Team. HMSO, London Report.

Lautanala, M. (1995) A Process Approach to Design for Construction. *Third Annual Conference of the International Group for Lean Construction*, 16-19 October 1995, Albuquerque, New Mexico. Reprinted in Alarcon, L. (1997) *Lean Construction*. A.A. Balkema, Rotterdam.

Leany, P.G. (1992) 'Design for Assembling'. Assembly Automation, vol. 12, no. 2, pgs. 8-17.

Li, H. & Love, P.E.D. (1999) 'Design Concept as a Model for Modelling Design Process and its Knowledge'. International Journal of Construction Information Technology, vol. 6, no. 1, pgs. 87-103.

Li, H. (1998) 'Petri Net as a Formalism to Assist Process Improvement in the Construction Industry'. Automation in Construction, vol. 7, pgs. 349-356.

Lloyd, P. & Scott, P. (1994) 'Discovering the Design Problem'. Design Studies, vol. 15, no. 2, pgs. 125-140.

Lloyd, P. & Deasley, P. (1998) 'Ethnographic Description of Design Networks'. Automation in Construction, vol. 7, no. 2/3, pgs. 101-110.

Love, P.E.D., Mohamed, S., Wyatt, A.D. & Tucker, S.N. (1996) Concurrent Engineering: A Multi-Disciplinary Approach For Construction. *Proceedings of the International Conference on Urban Engineering in Asian Cities in the 21st Century*, pgs. D.232-237.

Luiten, B. & Tolman, F. (199) Computer Aided DfC (Design for Construction) in the Building and Construction Industries. *Proceedings of Joint CIB Workshop on Computers and Information in Construction*, May 199, Montreal, Canada, Publication 165.

Machowski, F. & Dale, B.G. (1995) 'The Application of Quality Costing to Engineering Changes'. International Journal of Materials and Product Technology, vol. 10, no. 3-6, pgs. 378-388.

McGeorge, D. & Palmer, A. (1997) Consrtuciton Management: New Directions. Blackwell Science, Oxford.

Melhado, S.B. (1998) Designing for Lean Construction. *Sixth Annual Conference of the International Group for Lean Construction*, 13-15 August 1998, Guarujá, Brazil. http://www.ce.berkeley.edu/~tommelein/IGLC-6/ (August 1999).

Melles, B. (1994) What do we mean by Lean Production in construction? *Second Annual Conference of the International Group for Lean Construction*, 28-30 September 1994, Santiago, Chile. http://www.vtt.fi/rte/lean/ (September 1999).

Mohamed, S. & Tucker, S. (1996) 'Options for Applying BPR in the Australian Construction Industry'. International Journal of Project Management, vol. 14, no. 6, pgs. 379-385.

Moore, D. (1996(1)) 'The Renaissance: The Beginning of the End for Implicit Buildability'. Building Research and Information, vol. 24, no. 5, pgs. 259-269.

Moore, D. (1996(2)) 'Buildability Assessment and the Development of an Automated Design Aid for Managing the Transfer of Construction Process Knowledge'. Engineering Construction and Architectural Management, vol. 3, no. 1 / 2, pgs. 29-46.

Morris, D. & Brandon, J. (1993) *Re-engineering Your Business.* McGraw-Hill, New York, USA.

Moskowitz, H. & Kim, K.J. (1997) 'QFD Optimizer: A Novice Friendly Quality Function Deployment Decision Support System For Optomizing Product Designs'. Computers and Industrial Engineering, vol. 32, no. 3, pgs. 641-655.

O'Brien, B. (1995) *Decisions about Re-engineering: Briefings on Issues and Options.* Cahpman & Hall, UK.

O'Conner, J.T. (1985) 'Impacts of Constructability Improvement'. Journal of Construction Engineering and Management, vol. 111, no. 4, pgs. 404-410.

Oakland, J.S. & Oakland, S. (1997) Exploring Links Between Design and the Business Excellence Model. British Quality Foundation Report.

Obolensky, N. (1994) *Practical Business Re-engineering: Tools and Techniques for Achieving Effective Change.* Kogan Page, UK.

Ohno, T. (1978) 'Toyota Production System: Beyond Large Scale Production'. http://www.leanconstruction.org/papers.htm (August 1999).

Palmer, A. (1996) 'Holistic Appraisal of Value Engineering in Construction in United States'. Journal of Construction Engineering and Management, vol. 122, no. 4, pgs. 324-328.

Palmer, A. (1995) Value Management-Bridging the Cultural Gap. *Building for the 21st Century Proceedings of the Fith East Asia-Pacific Conference on Structural Engineering and Construction*, 25-27 July 1995, Gold Coast, Australia, pgs. 929-936.

Patty, B., McCullouch, B.G. & Vanegas, J.A. (1995) Automating Constructablitity During Design. *Construction Congress - Proceedings of the 1995 Conference*, 22-26 October 1995, San Diego, California, pgs. 331-338.

Proverbs, G.D., Holt, G.D. & Olomolaiye, P.O. (1999) 'Factors Impacting Construction Project Duration: A Comparison Between France, Germany and the U.K.'. Building and Environment, vol. 34, no. 2, pgs. 197-204.

Revelle, J.B., Moran, J.W. & Cox, C.A. (1998) *The QFD handbook.* Wiley, New York.

Rooke, J. & Seymour, D. (1995) 'The NEC and the Culture of the Industry: Some Early Findings Regarding Possible Sources of Resistance to Change'. Engineering, Construction and Architectural Management, vol. 4, pgs. 287-305.

Roozenburg, N. (1991) On the Logic of Innovative Design. Cross, N. (ed) (1992) *Research in Design Thinking. Proceedings of a Workshop held at the Faculty of Industrial Design Engineering,* Delft University of Technology, 29-31 May 199, pgs. 127-138.

Royal Institute of British Architects (RIBA) (1992) Standard Form of Agreement for the Appointment of an Architect. Royal Institute of British Architects, RIBA Publications, London.

Russell, J.S., Gugel, J.G. & Radtke, M.W. (March 1994) 'Comparative Analysis of Three Constructability Approaches'. Journal of Construction Engineering and Management, vol. 120, no. 1, pgs. 180-195.

Sanvido, S.A. (1990) An Integrated Building Process Model. Computer Integrated Research Program, Pennsylvania State University, Sponsored by National Science Foundation, Grant No. DMC-8717485.

Sanvido, V.E. & Medeiros, D. (1990) 'Computer-Integrated-Manufacturing Concepts to Construction'. Journal of Construction Engineering and Management, vol. 6, no. 3, pgs. 365-379.

Serpell, A. & Wagner, R. (1994) Application of Quality Function Deployment to the Determination of the Design Characteristics of Building Apartments. *Second Annual Conference of the International Group for Lean Construction,* 28-30 September 1994, Santiago, Chile. Reprinted in Alarcon, L. (1997*) Lean Construction.* A.A. Balkema, Rotterdam.

Sheath, D.M., Woolley, H., Cooper, R., Hinks, J. & Aouad, G. (1996) A Process for Change - the Development of a Generic Design Construction Process Protocol. *Proceedings of the International Construction Information Technology Conference (InCIT 96),* April 1996, Sydney, Australia.

Shingo, S. (1989) A Study of the Toyota Production System from an Industrial Engieering View Point. http://www.leanconstruction.org/papers.htm (September, 1999).

Suh, N.P. (1990) *The Principles of Design.* Oxford University Press, New York.

The Agile Construction Initiative (1998) Constructing the Best Government Client: Pilot Benchmarking Study. A report produced by the Agile Construction Initiative, University of Bath, for H.M. Treasury Procurement Group and the Government Construction Client Panel, October 1998.

The Construction Management Committee of the ASCE Construction Division (1991) 'Constructability and Constructability Programs: White Paper'. Journal of Construction Engineering and Management, vol. 117, no. 1, pgs. 67-89.

The Construction Task Force [Egan, J. – Chairman] (1998) Rethinking Construction. Department of Transport and Regions.

The Tavistock Institute (1999) Building Down Barriers: Interim Evaluation Report. The Concept Phase. The Tavistock Institute, March 1999.

Thomas, H.R. & Napolitan, C.L. (1995) 'Quantitative Effects on Construction Changes on Labor Productivity'. Journal of Constuction Engineering and Management, vol. 121, no. 3, pgs. 290-296.

Thomson, V.J. (1995) Process Monitoring for Continuous Improvement. Browne, J. & O'Sullivan, D. (eds) (1995) *Re-engineering the Enterprise.* Chapman & Hall, London, pgs. 294-301.

Tilley, P., Wyatt, A. & Mohamed, S. (1997) Indicators of Design and Documentation Deficiency. *Fifth Annual Conference of the International Group for Lean Construction*, 1997, Gold Coast, Australia. http://www.vtt.fi/rte/lean/ (September 1999).

Tommelein, I.D. (1997) Discrete event simulation of lean construction processes. *Fifth Annual Conference of the International Group for Lean Construction*, 1997, Gold Coast, Australia. http://www.vtt.fi/rte/lean/ (September 1999).

Towill, D.R. (1997) Enabling Construction as a Manufacturing Process. Innovation in Civil and Construction Engineering, pgs. 145-151.

Valkenburg, R.C. (1998) 'Shared Understanding as a Condition for Team Design'. Automation in Construction, vol. 7, no. 2 / 3, pgs. 111-121.

Visser, W. (1993) 'Collective Design: A Cognitive Analysis of Co-operation in Pracitce'. *Proceedings of the International Conference on Engineering Design*, 1993, pgs. 385-392.

Wallace, K. (1991) 'Some Observations on Design Thinking'. Cross, N. (ed) (1992) *Research in Design Thinking.* Delft University Press, Netherlands. *Proceedings of a Workshop held at the Faculty of Industrial Design Engineering*, Delft University of Technology, 29-31 May 1991, pgs. 75-86.

Womack, J.P., Jones, D. (1996) *Lean Thinking.* Simon & Schuster.

Yamigawa, Y. (1988) 'An assembly ease evaluation method for product designers'. DAC' Techno Jap., vol. 21, no. 12.

Yin, R.K. (1984) *Case Study Research: Design and Methods.* SAGE Publications, Bevely Hills, Calafornia.

BIBLIOGRAPHIC INFORMATION

Akin, O. & Akin, C. (1998) 'On the Process of Creativity in Puzzles, Inventions and Designs'. Automation in Construction, vol. 7, no. 2,3, pgs. 123-128.

Alshawi, M. (1995) 'A Framework for Integrating Business and Information Technology in Construction'. The International Journal of Civil Engineering Systems, vol. 12, pgs. 249-261.

Amor, R. & Clift, M. (1997) Documents as an Enabling Mechanism for Concurrent Engineering in Construction. *Concurrent Engineering in Construction - 1st International Conference*, 3-4 July 1997, London UK, pgs. 151-162.

Atkin, B. et al (1996) Benchmarking Best Practice Report - Construction Site Processes. Construct IT Centre, UK.

Atkin, B. et al (1996) Benchmarking Best Practice Report - Briefing and Design. Construct IT Centre, UK.

Augenbroe, G. (1994) Integrated Use of Building Design Tools: Results From the COMBINE Project. Tzonis, A. & White, I. (eds) (1994) *Automation Based Creative Design.*Elsevier Science, pgs. 205-235.

Ball, L.J., Maskill, L., & Ormerod, T.C. (1998) 'Satisficing in Engineering Design: Causes, Consequences and Implications for Design Support'. Automation in Construction, vol. 7, no. 2,3, pgs. 213-227.

Barrett, P. (1996) Context and Trends in the Construction Industry. *Proceedings of the 2nd COBRA Conference,*1996, University of West England.

Betts, M. & Wood-Harper, T. (1994) 'Re-engineering Construction: a New Management Research Agenda'. Construction Management and Economics, vol. 12, pgs. 551-556.

Bowen, P.A. (1995) The Effectiveness of the Briefing Process in the Attainment of Client Objectives for Construction Projects in South Africa. *Proceedings of the 1st COBRA Conference*, 8-9 September 1995, Heriot-Watt University.

Cairns, G.M. (1996) 'User Input to Deign: Confirming the 'User-Needs' Gap Model'. Environments by Design, vol. 1, no. 2, pgs. 125-140.

Christiaans, H. & Venselaar (1991) An Empirical Study into Design Thinking. Cross, N. (ed) (1992) *Research in Design Thinking. Proceedings of a Workshop held at the Faculty of Industrial Design Engineering,* Delft University of Technology, 29-31 May 1991, pgs. 119-125.

Clift, M. & Amor, R. (1997) Concurrent Engineering Support with an Advanced DMS. *4th International Conference on Concurrent Enterprising,* 8-10 October 1997, Nottingham UK, pgs. 55-64.

Cross, N. (1985) 'Styles of Learning, Designing and Computing'. Design Studies, vol. 6, no. 3, pgs. 157-162.

Eastman, C.M. & Fereshatian, N. (1994) 'Information Models for Use in Product Design: a Comparison'. Computer - Aided Design, vol. 26, no. 7, pgs. 551-572.

Evans, G.N. et al (1997) 'Organising for Improved Construction Interfaces'. Innovation in Civil and Construction Engineering, pgs. 207-212.

Evans, G.N. et al (1997) 'Process Costing - The Route to Construction Reengineering'. *Innovation in Civil and Construction Engineering,* pgs. 153-162.

Evbuomwan, N.F.O. & Anumba, C. (1995) 'Concurrent Lifecycle Design and Construction'. Development in Computer Aided Design and Modelling for Civil Engineering, pgs. 93-102.

Fazio, P. & Bedardn(1992) Constraints for Generating Building Envelope Design Alternatives. Kalay, Y.E. (ed) (1992) *Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 145-156.

Fenves, S.J. (1992) Performance Evaluation in an Integrated Software Environment for Building Design and Construction Planning. Kalay, Y.E. (ed) (1992) *Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 159-169.

Fowler, C. (1995) Business Process Re-engineering in the Construction Industry: A Production Engineering Tool. *COBRA 95 RICS Construction and Building Research Conference,* 8-9 September 1995, Heriot-Watt University, UK, pgs. 217-223.

Franceschini, F. & Rossetto (1995) 'QFD: The Problem of Comparing Technical / Engineering Design Requirment'. Research in Engineering Design, vol. 7, no. 4, pgs. 270-278.

Gibson, G.E. et al (1996) 'Constructability in Public Sector'. Journal of Construction Engineering and Management, vol. 122, no. 3, pgs. 274-280.

Goel, V. & Pirolli (1989) 'Motivating the Notion of Generic Design Within Information Processing Theory: The Design Problem Space'. AI Magazine, vol. 10, no. 1, pgs. 18-36.

Goldschmidt, G. (1991) 'The Dialectics of Sketching'. Creativity Research Journal, vol. 4, no. 2, pgs. 123-143.

Gross, M. (1984) 'Design as the Exploration of Constraints'. Design Studies, vol. 5, no. 3, pgs. 137-138.

Hacfoort, E.J.H. & Veldhuisen (1992) A Building Design and Evaluation System. Kalay, Y.E. (ed) (1992*) Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 195-211.

Hanlon, E.J. & Sanvido (1995) 'Constructability Information Classification Scheme'. Journal of Construction Engineering and Management, vol. 121, no. 4, pgs. 337-345.

Hazelhurst, G. (1995) Re-engineering the Processes of Construction Engineeering and Design: Islands of Automation and Integration. *COBRA 95 RICS Construction and Building Research Conference*, 8-9 September 1995, Heriot-Watt University, UK, pgs. 207215.

Hennessey, J.M. (1994) The Ideate Project: Exploring Computer Enhancements for Conceptualizing. Tzonis, A. & White, I. (eds) (1994) *Automation Based Creative Design.* Elsevier Science, pgs. 349-362.

Ho, S. (1995) 'Business Process Redesign and Value Analysis'. Quality World, vol. 22, no. 5, pgs. 322-327.

Huovila, P. & Seren, K-J. (1995) Customer-Oriented Design Methods for Construction Projects. *International Conference on Engineering Design*, 22-24 August 1995, Praha, pgs. 444-449.

Ireland, V. (1994) T40 Process Re-engineering in Construction. Technical Report: Fletcher Construction, Australia.

Kaneta, T. et al (1997) Structural Analysis of Design and Construction Process of Building - Towards Concurrent Engineering. *Proceedings of 1st Conference of Concurrent Engineering in Construction*, 3-4 July 1997, London, pgs. 77-86.

Koppelaar, H. (1991) On Design Automation. Cross, N. (ed) (1992*) Research in Design Thinking. Proceedings of a Workshop held at the Faculty of Industrial Design Engineering,* Delft University of Technology, 29-31 May 1991, pgs. 165-176.

Krouwel, P. (1992) Design Thinking in Practice. Cross, N. (ed) (1992*) Research in Design Thinking. Proceedings of a Workshop held at the Faculty of Industrial Design Engineering,* Delft University of Technology, 29-31 May 1991, pgs. 11-19.

Liggett, R.S. Mitchell & Tan (1992) Multilevel Analysis and Optimization of Design. Kalay, Y.E. (ed) (1992*) Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 251-269.

Love, P.E.D. (1996) 'Construction Process Re-Engineering and the Australian Construction Industry'. The Austrailian Institute of Building Papers, vol. 7, pgs. 13-23.

Love, P.E.D. & Li, H. (1998) 'From BPR to CPR - Conceptualising Re-engineering in Construction'. Business Process Management Journal, vol. 4, no. 4, pgs. 291-305.

Love, P.E.D. & Mohamed, S Tucker, S.N. (1997) A Conceptual Approach for Re-engineering the Construction Process. Mohamed, S. (ed) (1997) *Consruction Process Re-engineering.* pgs. 13-23.

Love, P.E.D., Mohamed, S., Wyatt, A.D. & Tucker, S.N. (1996) Concurrent Engineering: A Multi-Disciplinary Approach For Construction. *Proceedings of the International Conference on Urban Engineering in Asian Cities in the 21st Century*, November 1996, pgs. D.232-237.

Madanshetty, S.I. (1995) 'Cognitive Basis for Conceptual Design'. Research in Engineering Design, vol. 7, no. 4, pgs. 232-240.

Mahdavi, A. & Suter, G. (1998) 'On the Implications of Design Process Views for the Development of Computational Design Support Tools'. Automation in Construction, vol. 7, no. 2,3, pgs. 189-204.

Manning, P. & Mattar (1992) A Preliminary To Development of Expert Systems For Total Design of Entire Buildings. Kalay, Y.E. (ed) (1992*) Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 213-237.

Mazijoglou, M. & Scrivener, S.A.R. (1998) 'The Rich Picture of Design Activity'. Automation in Construction, vol. 7, no. 2,3, pgs. 157-175.

McGeorge, D. (1995) The Application of Computer Generated Graphics in Organisational Decision Support Systems Operating in a Real Time Mode. *Proceedings of the 1st COBRA Conference*, 8-9 September 1995, Heriot-Watt University, pgs. 163-171.

Mitchell, W.J. (1992) Introduction: The Uses of Inconsistency in Design. Kalay, Y.E. (ed) (1992*) Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 1-13.

Mohamed, S. (1997) BPR Critic - CPR Advocate. Mohamed, S. (ed) (1997) *Consruction Process Re-engineering*, pgs. 25-37.

Otto, K.N. (1995) 'Measurement Methods for Product Evaluation'. Research in Engineering Design, vol. 7, no. 2, pgs. 86-101.

Pollalis, S.N. (1994) Towards the Automation of Conceptual Design. Tzonis, A. & White, I. (eds) (1994) *Automation Based Creative Design.* Elsevier Science, pgs. 429-445.

Schmitt, G. (1992) Design for Performance. Kalay, Y.E. (ed) (1992*) Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 83-100.

Schon, D.A. (1984) 'Problems, Frames and Perspectives on Designing'. Design Studies, vol. 5, no. 3, pgs. 132-136.

Serpell, A. & Wagner, R. (1994) Application of Quality Function Deployment to the Determination of the Design Characteristics of Building Apartments. *Second Annual Conference of the International Group for Lean Construction,* 28-30 September 1994, Santiago, Chile. Reprinted in Alarcon, L. (1997) *Lean Construction.* A.A. Balkema, Rotterdam.

Sidwell, A.C., Lenard, D., Tucker, S.N. & Ambrose, M.D. (1997) Re-engineering the Construction Project Delivery Process. Mohamed, S. (ed) (1997) Consruction Process Re-engineering, pgs. 169-180.

Smith, J., Kenley, R. & Wyatt, R. (1998) 'Evaluating the Client Briefing Problem: An Exploratory Study'. Engineering, Construction and Architectural Management, vol. 5, no. 4, pgs. 387-398.

Tang, M.X. (1995) Development of An Integrated AI System for Conceptual Design Support. AI System Support For Conceptual Design. *Preceedings of the International Workshop on Engineering Design,* 1995, Lancaster, pgs. 153-169.

Tovey, M. (1991) Automotive Stylists' Design Thinking: Visual Creativity and CAD. Cross, N. (ed) (1992*) Research in Design Thinking. Proceedings of a Workshop held at the Faculty of Industrial Design Engineering,* Delft University of Technology, 29-31 May 1991, pgs. 87-97.

Turk, Z. (1997) A Framework for the Engineering Information Technologies. *4th International Conference on Concurrent Enterprising,* 8-10 October 1997 Nottingham UK, pgs. 257-268.

Vanegas, J. & Nguyen (1997) A Global System of Acquisition and Dissemination of Lessons Learned. *Construction Congress V - Managing Engineered Construction in Expanding Global Markets - Proceedings of Conference,* 1997, pgs. 494-501.

Visser, W. (1993) Collective Design: A Cognitive Analysis of Co-operation in Pracitce. *Proceedings of the International Conference on Engineering Design,* 1993, pgs. 385-392.

Walsh, V. & Roy (1985) 'The Designer as 'Gatekeeper' in Manufacturing Industry'. Design Studies, vol. 6, no. 3, pgs. 127-156.

Whitney, D. (1990) 'Designing the Design Process'. Research in Engineering Design, vol. 2, no. 1, pgs. 3-13.

Wiezel, A. & Becker (1992) Integration of Performance Evaluation in Computer-Aided Design. Kalay, Y.E. (ed) (1992*) Principles of Computer-Aided Design: Evaluating and Predicting Design Performance.* Wiley Inter-Science, pgs. 171-181.

Some Useful URLs

Construction Management / Process Improvement Institutions

UK

Bath University – Agile Construction Initiative
http://www.bath.ac.uk/Departments/Management/research/agile/home.htm (June 1999)

Salford University – Department of Surveying
http://www.salford.ac.uk/survey/ (June 1999)

Reading University – Construction Management and Engineering
http://www.construct.rdg.ac.uk/ (June 1999)

South Bank University – Construction Management Research Group
http://www.pse.sbu.ac.uk/cmrg/Default.htm (June 1999)

Loughborough University – Department of Civil and Building Engineering
http://www.lut.ac.uk/departments/cv/ (June 1999)

Finland

Technical Research Centre in Finland (VTT)
http://www.vtt.fi/cic/projects/star/star.html (June 1999)

Australia

Newcastle University
Gold Coast University
Griffith University

Australia's Commonwealth Scientific and Industrial Research Organisation (CSRIO) Building, Construction & Engineering
http://www.dbce.csiro.au/ (June 1999)

Construction Industry Institute (CII)
http://www.unisa.edu.au/construction/ (June 1999)

Lean Construction

International Group for Lean Construction
http://www.vtt.fi/rte/lean/ (June 1999)
Based in Finland

Lean Construction Institute
http://www.leanconstruction.org/ (June 1999)
USA Branch of above (same people)

Lean Institutes (Other than Construction)

Lean Enterprise Research Centre (Cardiff University)
http://www.cardiff.ac.uk/uwcc/carbs/lerc/links.html (June 1999)

Lean Enterprise Europe
http://www.leaneuro.co.uk/ (June 1999)

Lean Enterprise Institute
http://www.lean.org/

Construction Management Research Groups / Organisations

International Council for Research and Innovation in Building and Construction (CIB)
http://www.cibworld.nl/ (June 1999)

Association of Researchers in Construction Management (ARCOM)
http://www.rdg.ac.uk./AcaDepts/kc/ARCOM/intro.html (June 1999)

Construction Industry Research and Information Association (CIRIA)
http://www.ciria.org.uk/index.htm (June 1999)

European Construction Institute
http://info.lut.ac.uk/departments/cv/eci/index.html?39,27 (June 1999)

Building Research Establishment UK
http://www.bre.co.uk/ (June 1999)

APPENDIX A

List of Tables

Table A.1 – Cranfield and Heathrow Building Details and Construction Planning 2
Table A.2 – Cranfield and Heathrow Design Features and Construction Stage 3
Table A.3 – Preston and Aylesbury Building Details and Construction Planning 4
Table A.4 – Preston and Aylesbury Design Features and Construction Stage 5

Building Details

Name of Building		**Cranfield University Library**	**Heathrow Cargo Building 549**
Project Type		Construction	Construction
Building Type		Public sector	Commercial for let / lease
Location		Home Counties	Heathrow Airport
Floor Area		3000 m^2	Warehouses - 4400 m^2 Offices - 2100 m^2
Height		11 m	-
No. of Storeys		3	Offices - 4
Type of Construction	Brick		
	Steel Frame	✓	✓
	Concrete Frame	In-situ concrete sub-structure and columns	
	Cladding	✓	Profiled steel
	Roof Type	Steel truss	Kalzip aluminum
	Distinctive Features		60m span trusses to warehouse. Elevated transfer vehicle

Construction Planning

Type of Contract		Management contract	JCT
Length of Phase	Planned Construction	13 months	9 months
	Pre-eng.	6 months	Steel frame components fabricated off-site during construction phase
Time of Introduction to Project of Disciplines	Structural Engineer	Same time as Architect	12 months after Architect
	Quantity Surveyor	Before Architect	10 months after Architect
	M&E Consult.	1 month after Architect	14 months after Architect
	Others		Contractor - 17 months after Architect
Approx. Balance of Work (By Value)	Off-site	45.7%	-
	On-site	54.3%	-
No. of Contractors		22 (Inc. management contractor)	-
No. of Work Packages		21	-

Table A.1 – Cranfield and Heathrow Building Details and Construction Planning

Design Features

Level of Innovation	Design	Medium	Medium***
	Materials	Low	Medium***
	Assembly	Medium	Medium
Level of Architect Output from CAD to Main Contractors		None	None

Construction Stage

Site Access		Easy				Difficult			
Building Access (For Fit-out Phase)		Easy				Easy			
Compliance to Programme	Work Package	Curtain Walling	Block* Work	Fit-** out	Mechanical Services	Steel Frame	Cladding	Fit-out	Mechanical Services
	Time Over (wks)	4	4	3	6 (delay)	1	1	0	0
	Programme Length (mths)	2½	3	3		-	-	-	-
	Cost	-	-	-	-	-	-	-	-
Labour Turnover		Not known				Not known			
No. of AI's Issued									Cost
		295				174 AI's issued			£6,782
						45 Struct. RFI's			£3,036
						31 Mech. RFI's			£3,200
						17 Elect. RFI's			£1,300
						13 Public Health RFI's			£2,350
Key Personnel Who Worked Together on Previous Projects		Not known				All new personnel on this project			

* Delay caused by delay in curtain walling

** Part of delay caused by delay in curtain walling

*** Building has a high energy efficiency

Table A.2 – Cranfield and Heathrow Design Features and Construction Stage

Building Details

Name of Building		**Marks & Spencer**	**Aylesbury Shopping Centre**
Project Type		Refurbishment / Extension	
Building Type		Retail	Retail
Location		Preston - Lancashire	Aylesbury, Buckinghamshire
Floor Area		966m^2 - Extension 5110m^2 - Refurb.	44219m2
Height		-	23m
No. of Storeys		3	4
Type of Construction	Brick		✓
	Steel Frame	✓ (encased in concrete)	✓
	Concrete Frame		In-situ concrete sub-structure and columns to Mall Level
	Cladding	Brick / stonework front	✓
	Roof Type	Flat asphalt on concrete	Steel Suspension Structure
	Distinctive Features		

Construction Planning

Type of Contract		Marks & Spencer Design & Construct - Version 1	Management Contract
Length of Phase	Planned Construction	27 weeks	28 months
	Pre-eng.	11 weeks	12 months
Time of Introduction to Project of Disciplines	Structural Engineer	Pre-tender	At feasibility stage
	Quantity Surveyor	Pre-tender	At feasibility stage
	M&E Consult.	Pre-tender	At feasibility stage
	Others	Architect - Pre-tender	Architect at feasibility stage
Approx. Balance of Work (By Value)	Off-site	30%	£8,026,450
	On-site	70%	£13,595,550
No. of Contractors		39	52
No. of Work Packages		39	84

Table A.3 – Preston and Aylesbury Building Details and Construction Planning

Design Features

Level of Innovation	Design	Medium	Medium
	Materials	Low	Medium
	Assembly	Medium	Medium
Level of Architect Output from CAD to Main Contractors		All drawings by CAD - detailed sketches produced on-site by hand	None

Construction Stage

Site Access		Difficult	Difficult			
Building Access (For Fit-out Phase)		Difficult	Easy			
Compliance to Programme	Work Package	Generally satisfactory	Brickwork	Roof	External Cladding	Mechanical Services
	Time Over (wks)	2 - delay to contract	4wk	8wk	-	12wk
	Programme Length (mths)	-	-	-	-	-
	Cost	£150k - to TW	£1.65m	£0.146m	£0.519m	£4.35m
Labour Turnover		N / A	Not known			
No. of AI's Issued		41 VORF's issued	877 AI's Including 607 site directions			

Key Personnel Who Worked Together on Previous Projects	TW Commercial Mang. & TW Project Mang. M & S Project Mang. & TW Project Mang. TW Commercial Mang. & Assist. Quantity Surveyor	Architect & Quantity Surveyor

Table A.4 – Preston and Aylesbury Design Features and Construction Stage

[BLANK PAGE]

APPENDIX B

List of Figures

Figure B.1 – Change Order Costs: Work Package & Originator 2
Figure B.2 – Change Order Costs: Reason & Originator 2
Figure B.3 – Change Order Costs: Work Package & Reason 3
Figure B.4 – Fractional Cost of Change Orders for Each Work Package 3
Figure B.5 – Number of Change Orders Affecting Each Work Package 4
Figure B.6 – Number of Change Orders Specifying Each Reason Category 4
Figure B.7 – WP 1000: Preliminaries, Management Fees, etc 5
Figure B.8 – WP 3010: Substructure and Concrete Frame 5
Figure B.9 – WP 4010: Roof Steelwork and Perimeter Columns 6
Figure B.10 – WP 4020: Roofing 6
Figure B.11 – WP 4030: Curtain Walling 7
Figure B.12 - WP 5010: Blockwork/Partitions 7
Figure B.13 - WP 5020: Suspended Ceilings 8
Figure B.14 – WP 5050: Architectural Metalwork 8
Figure B.15 – WP 5060: Furnishings Fit-out 9
Figure B.16 – WP 5061: Carols and Shelving 9
Figure B.17 – WP 6010: Electrical Services 10
Figure B.18 – WP 6020: IT/Communications 10
Figure B.19 – WP 7010: Mechanical Services 11
Figure B.20 – WP8010: Lifts 11
Figure B.21 – WP 9010 – Landscaping/Drainage 12
Figure B.22 – Change Order Request Costs: All Change Orders Over the Entire Period When Change Orders Were Used 12
Figure B.23 – Cumulative Cost of All Change Orders Over the Entire Period When Change Orders Were Used 13
Figure B.24 – Distribution of Change Order Costs: Raw Data 13
Figure B.24b – Distribution of Change Order Costs: Raw Data (-£2000 to £2000) 14
Figure B.25 – Distribution of Change Order Costs: Cost Class Intervals of £500 14

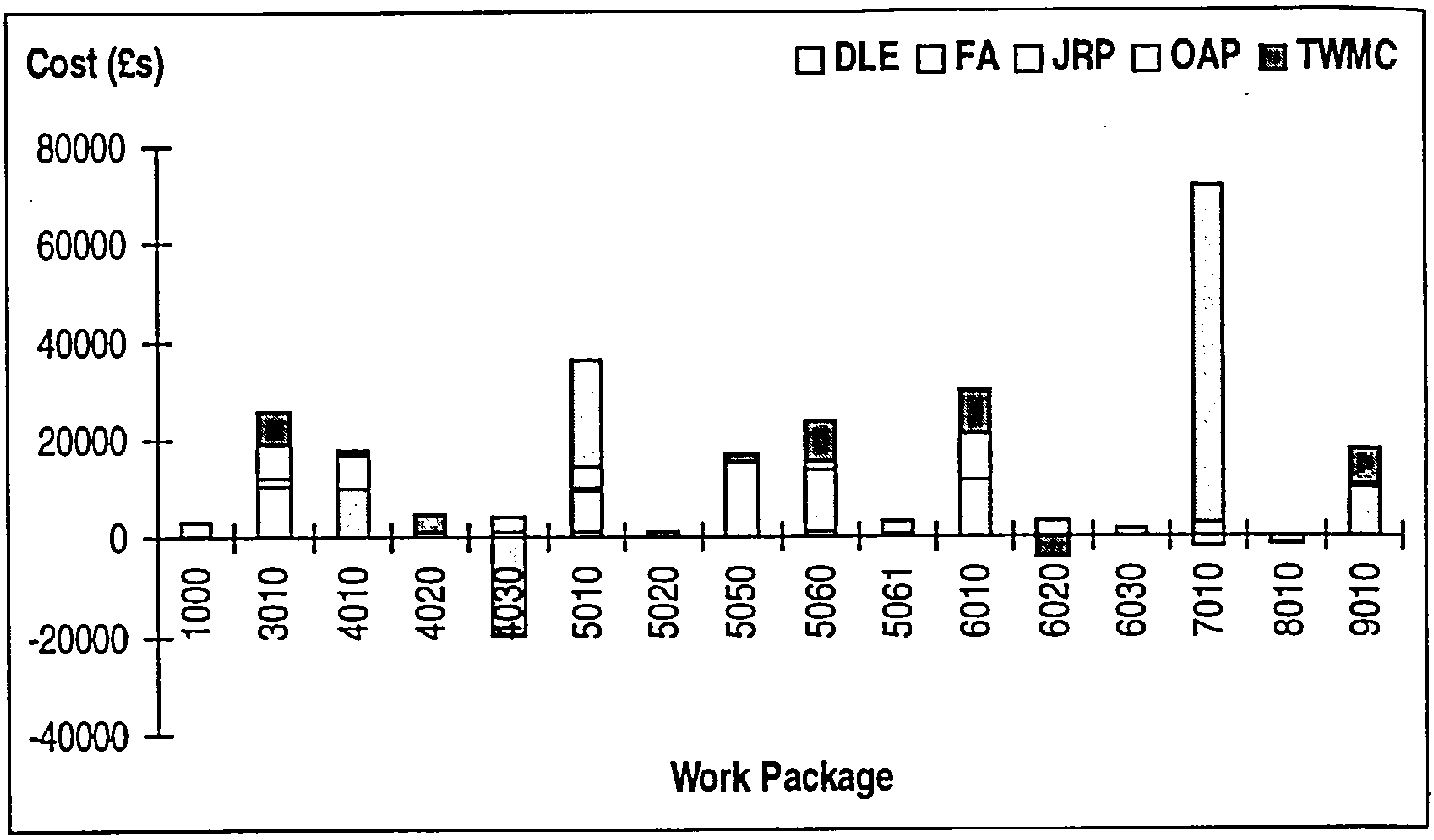


Figure B.1 – Change Order Costs: Work Package & Originator

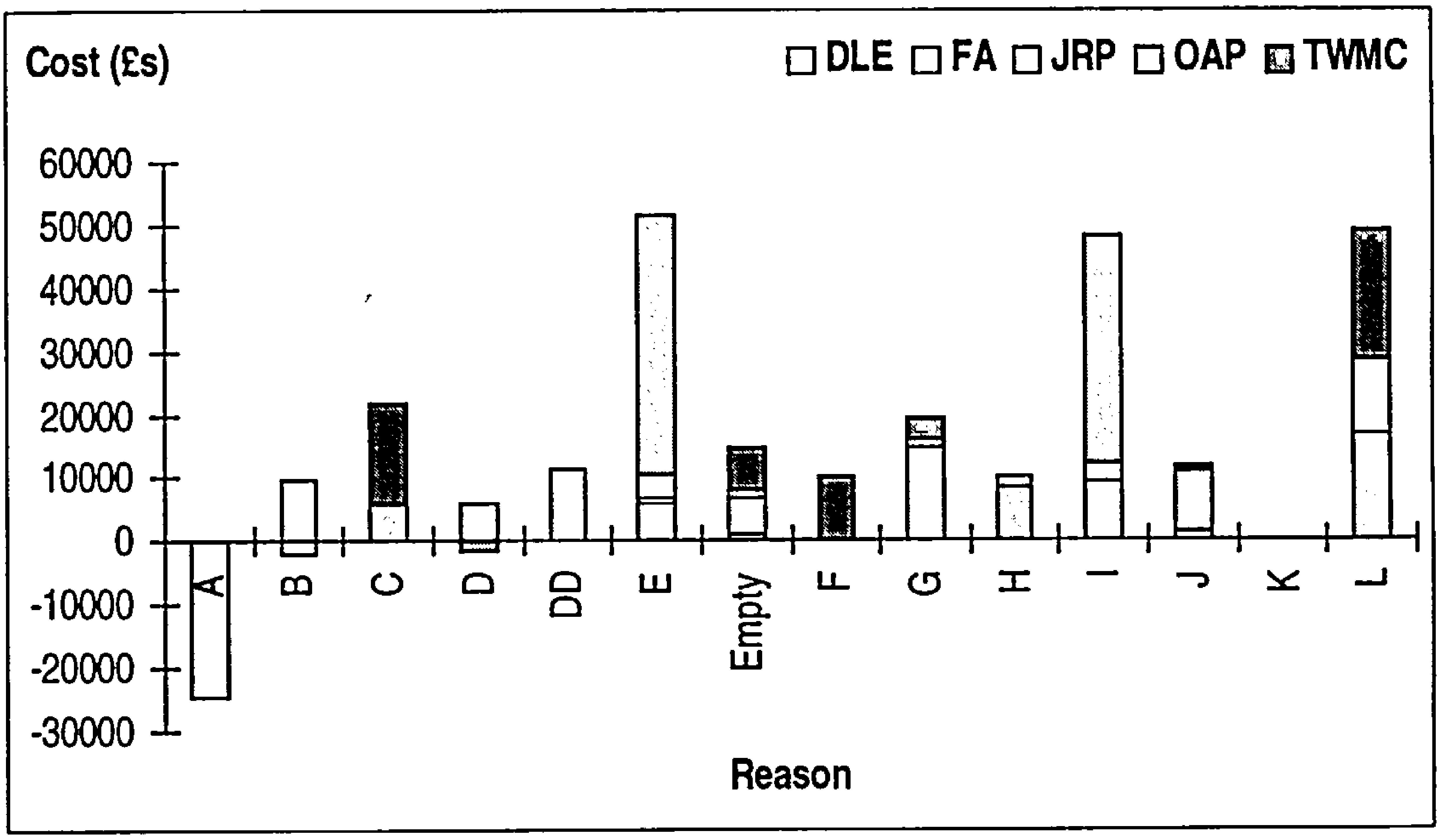


Figure B.2 – Change Order Costs: Reason & Originator

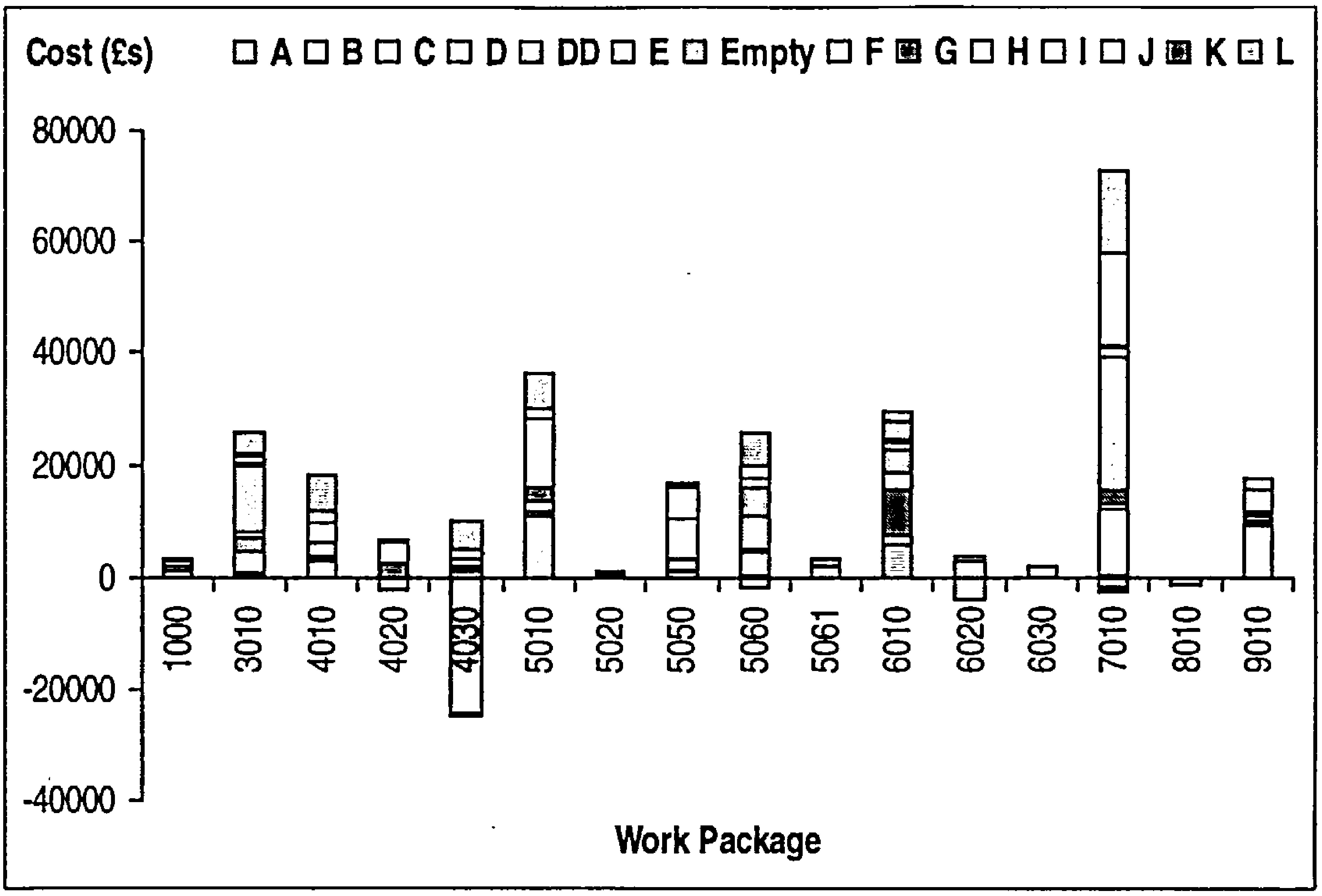


Figure B.3 – Change Order Costs: Work Package & Reason

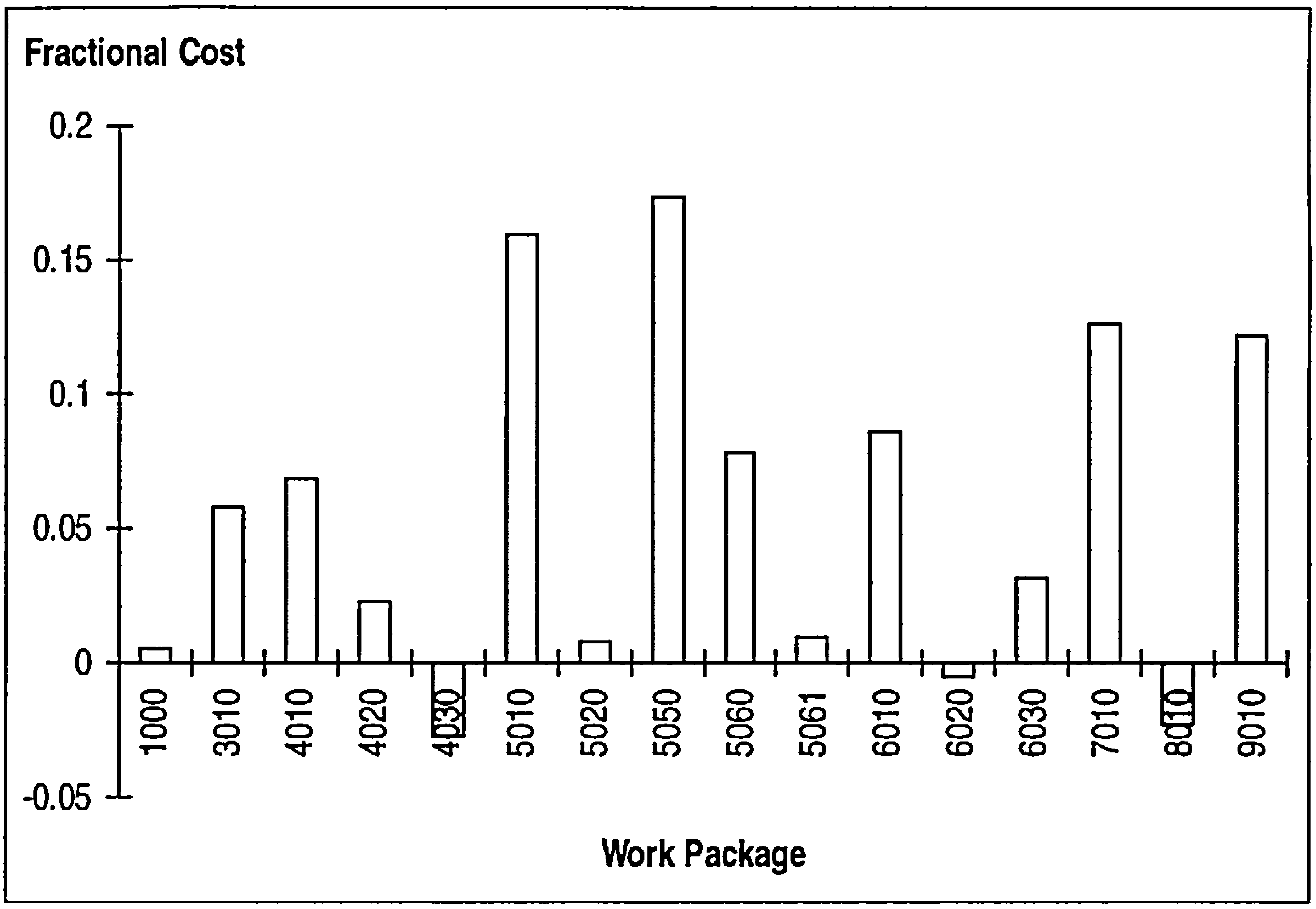


Figure B.4 – Fractional Cost of Change Orders for Each Work Package

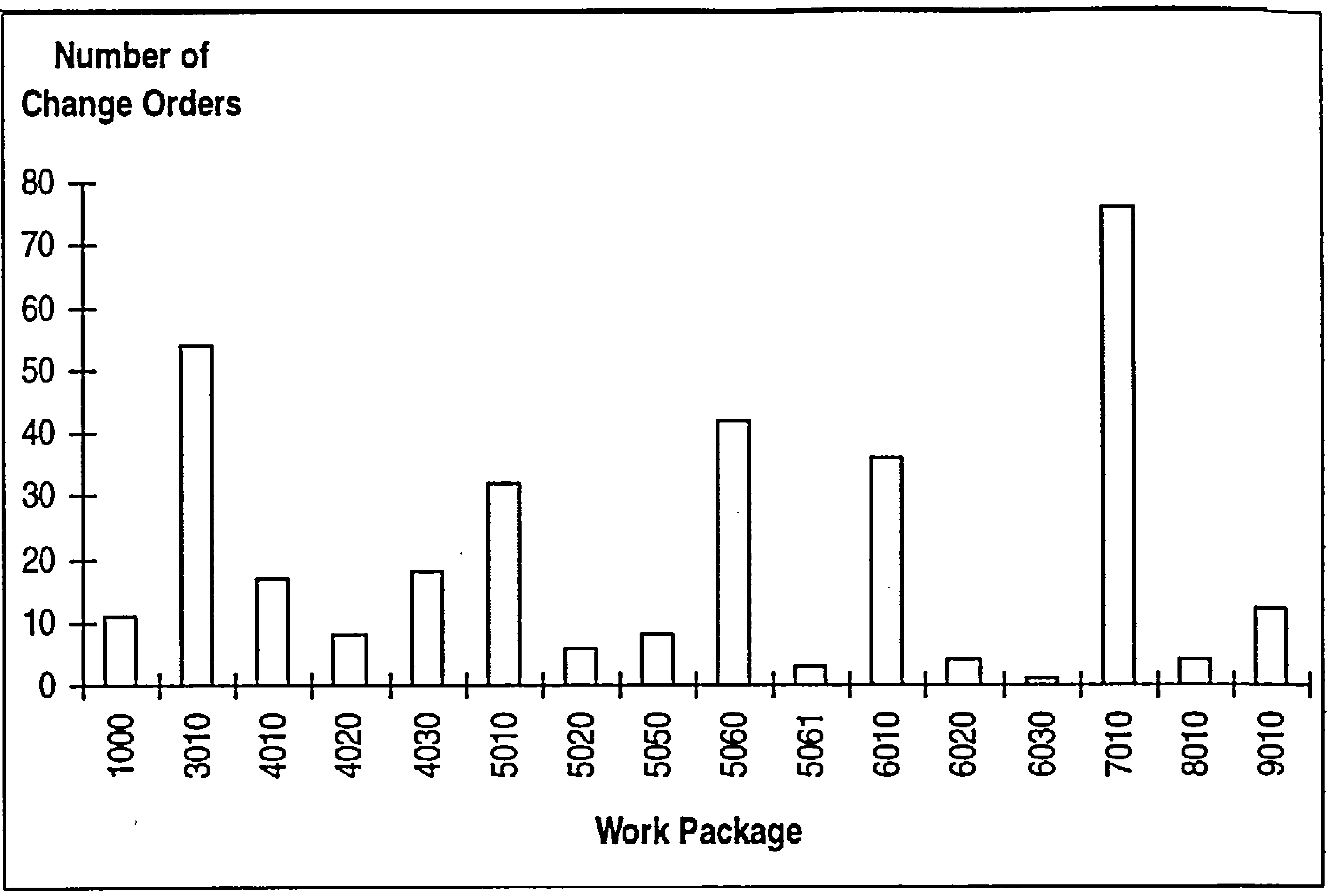


Figure B.5 – Number of Change Orders Affecting Each Work Package

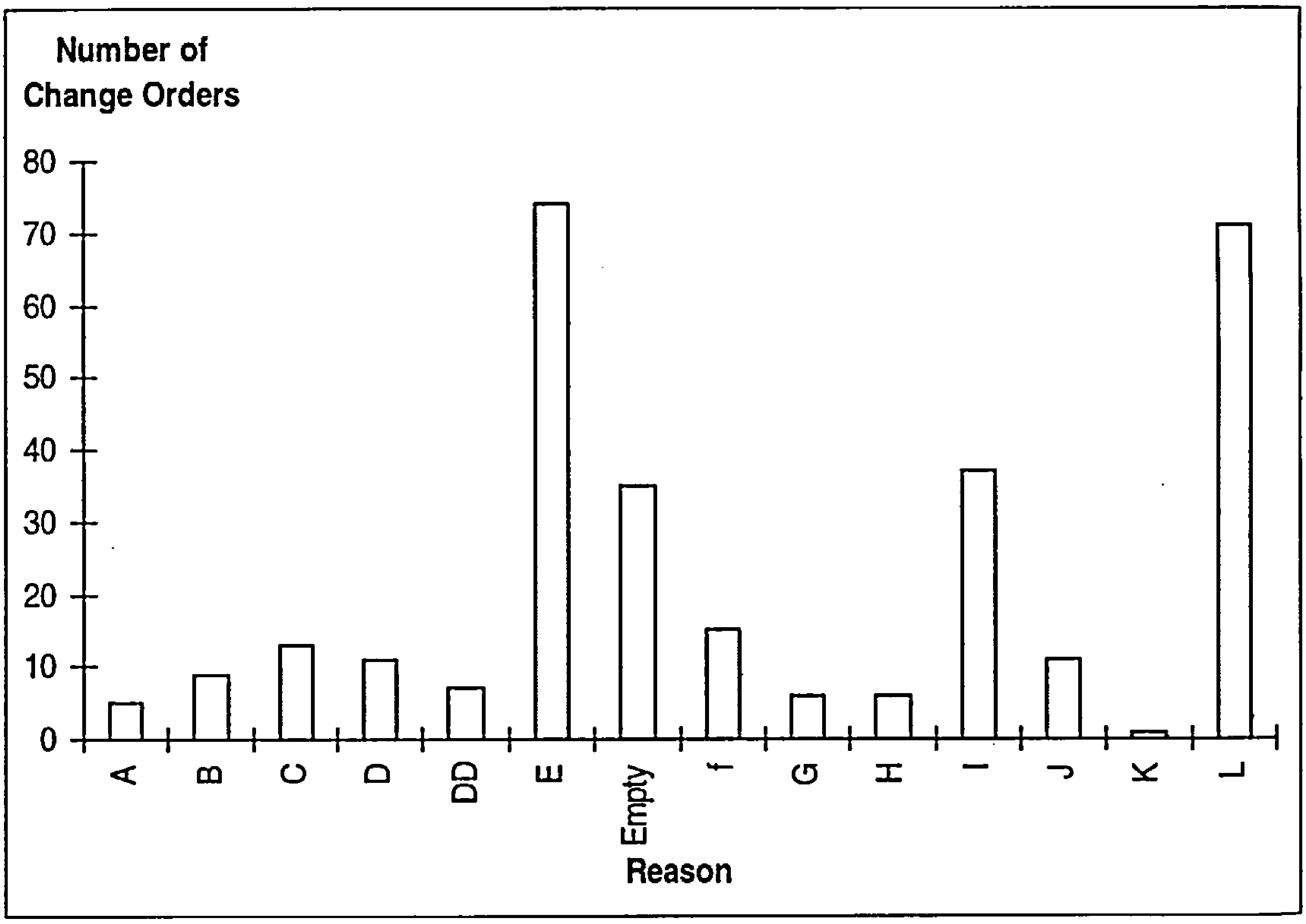


Figure B.6 – Number of Change Orders Specifying Each Reason Category

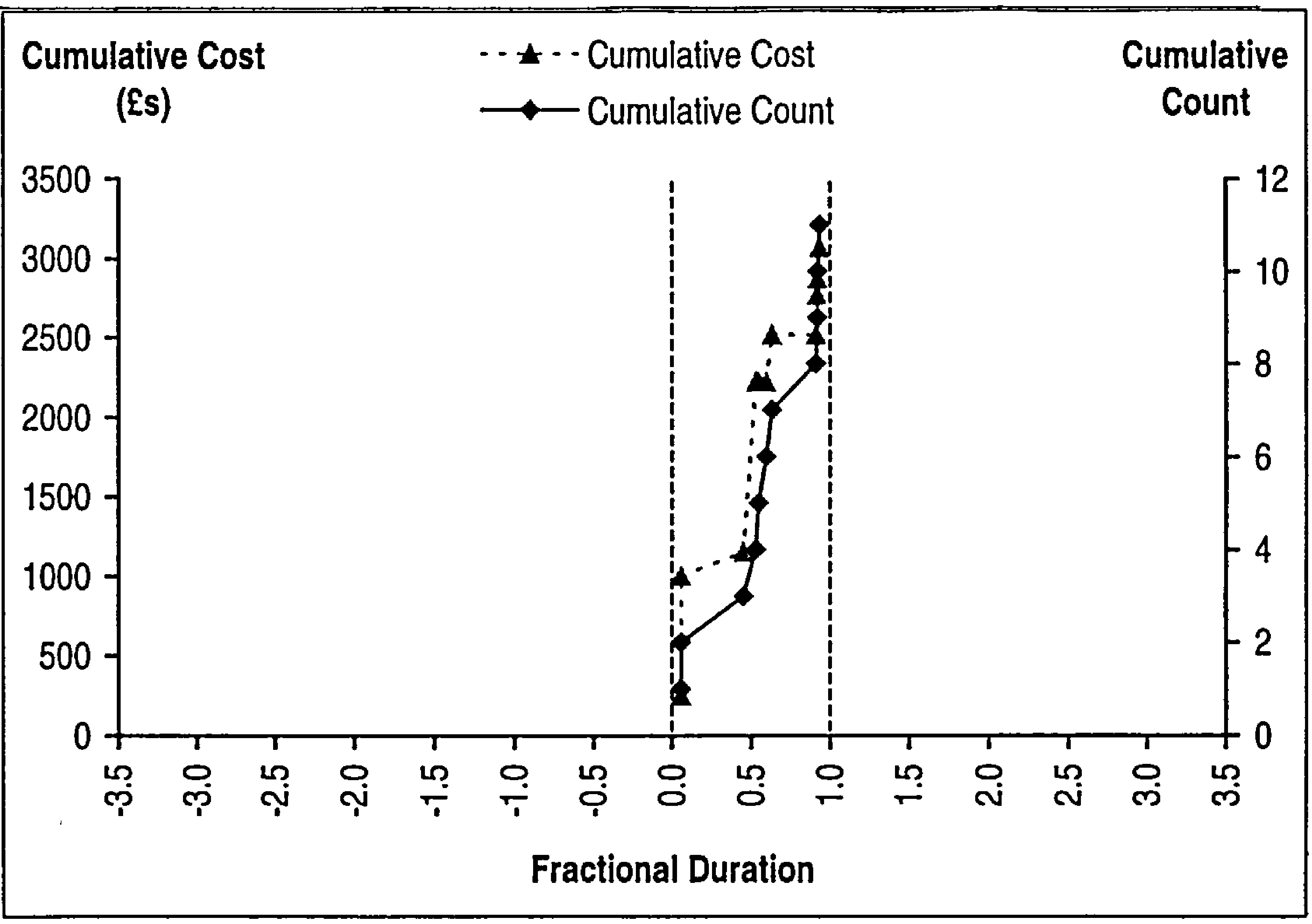


Figure B.7 – WP 1000: Preliminaries, Management Fees, etc

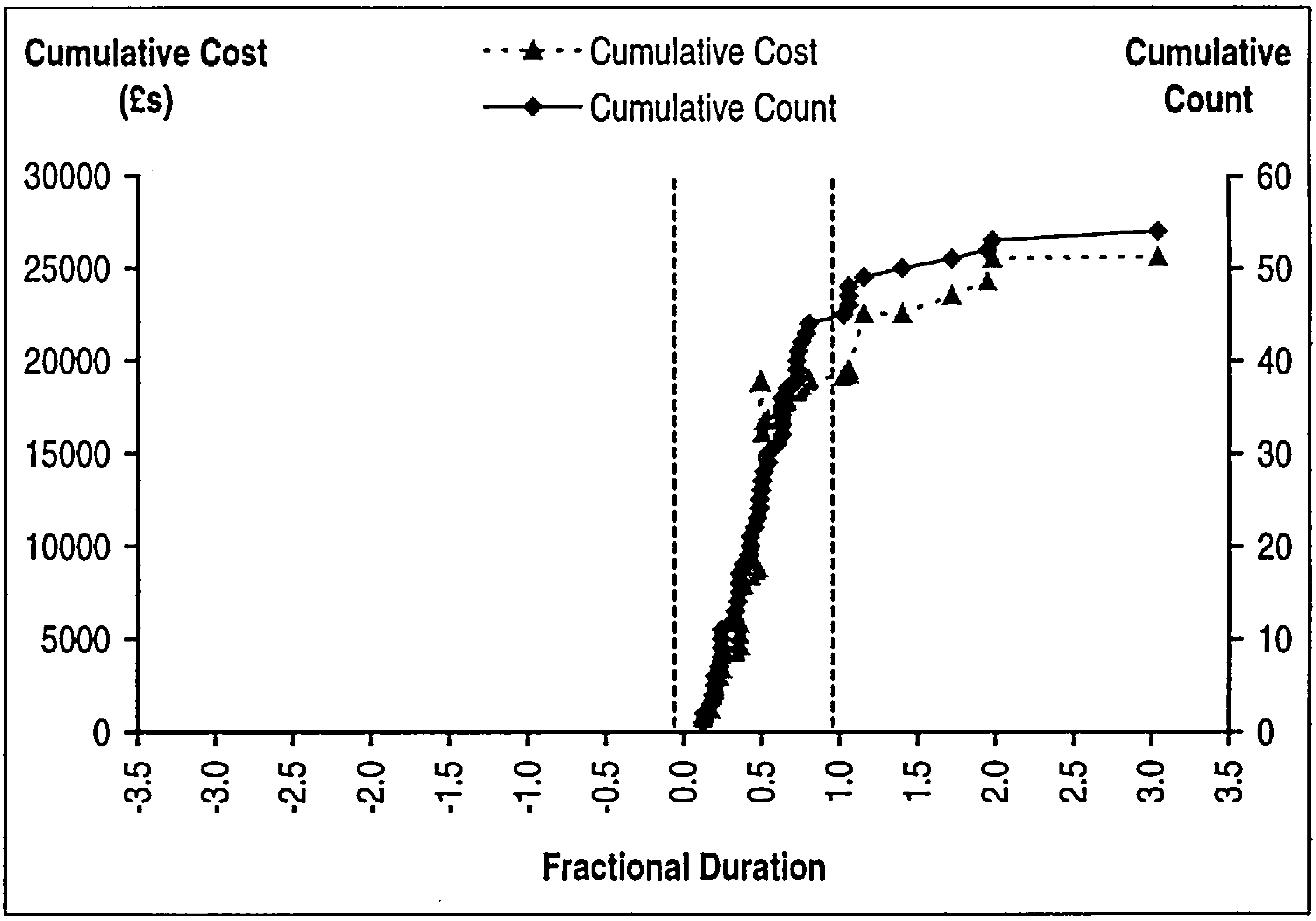


Figure B.8 – WP 3010: Substructure and Concrete Frame

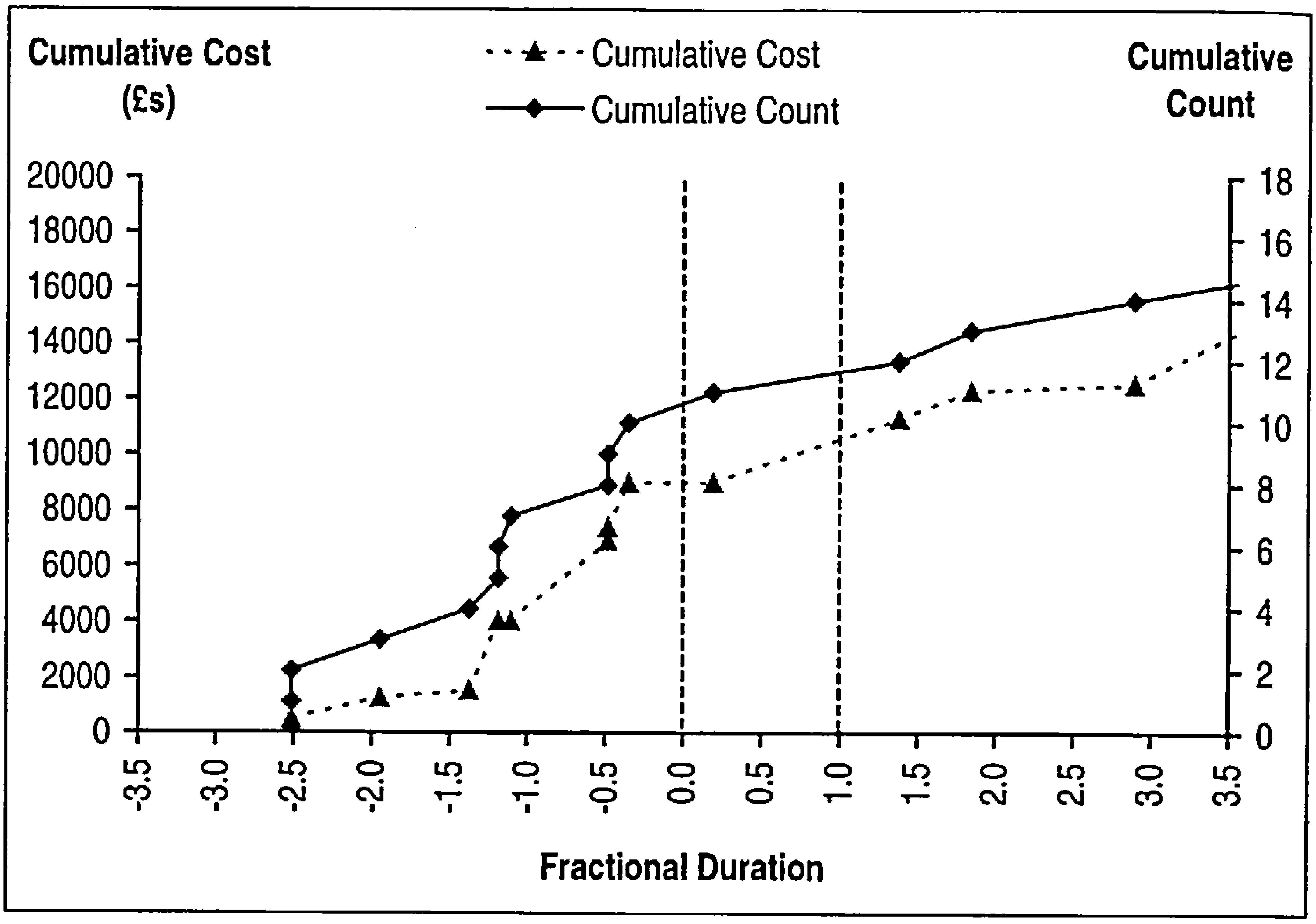


Figure B.9 – WP 4010: Roof Steelwork and Perimeter Columns

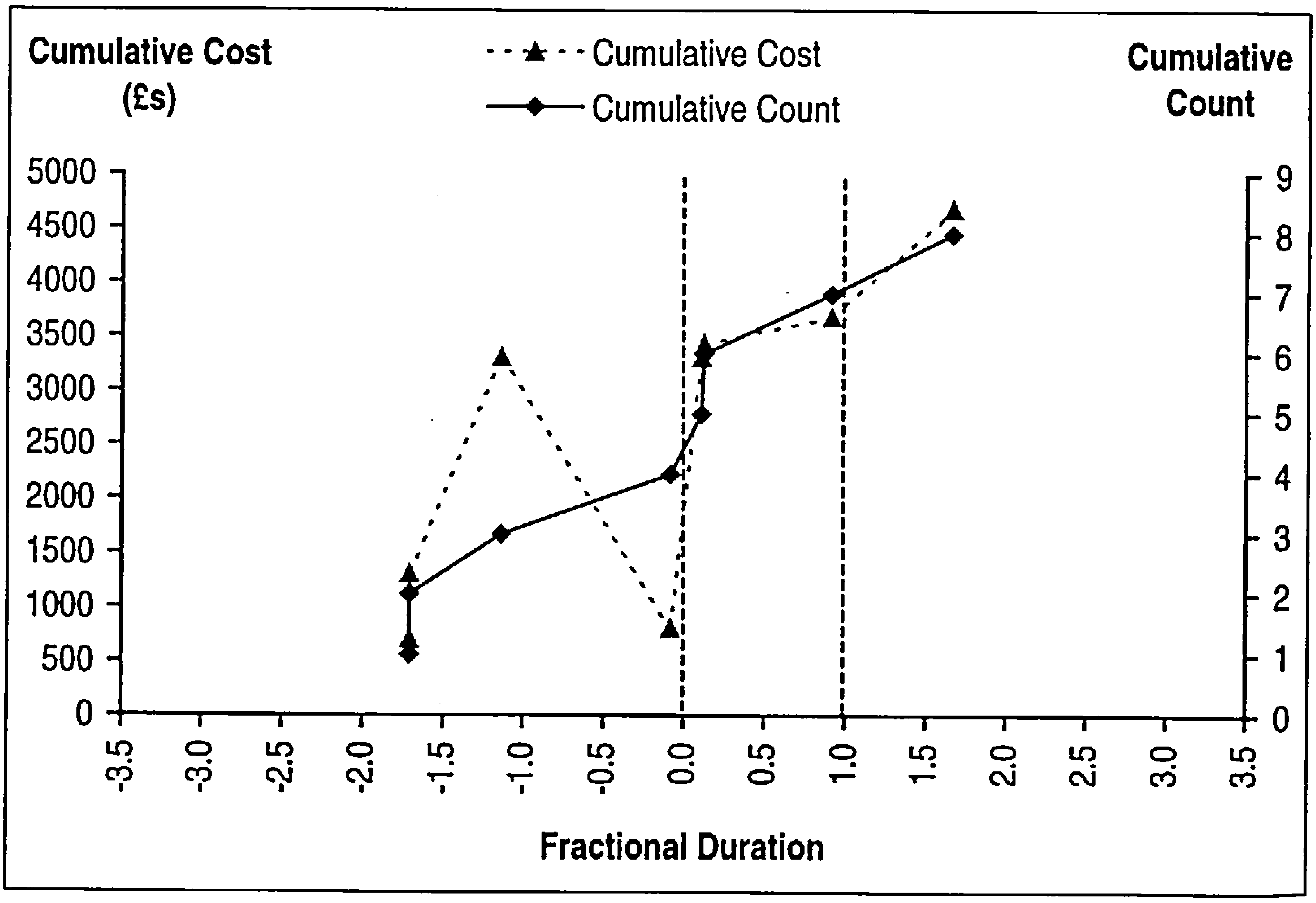


Figure B.10 – WP 4020: Roofing

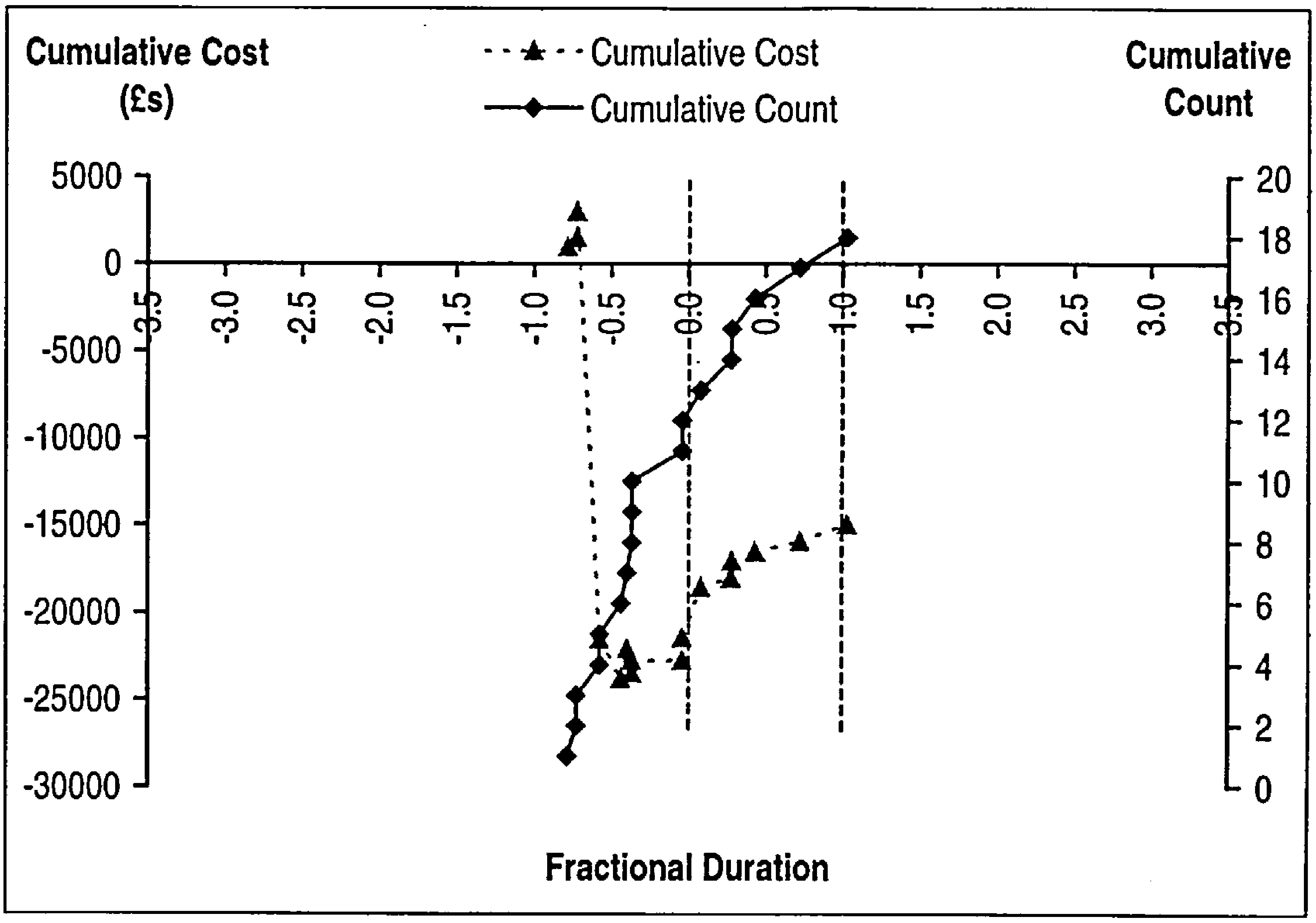


Figure B.11 – WP 4030: Curtain Walling

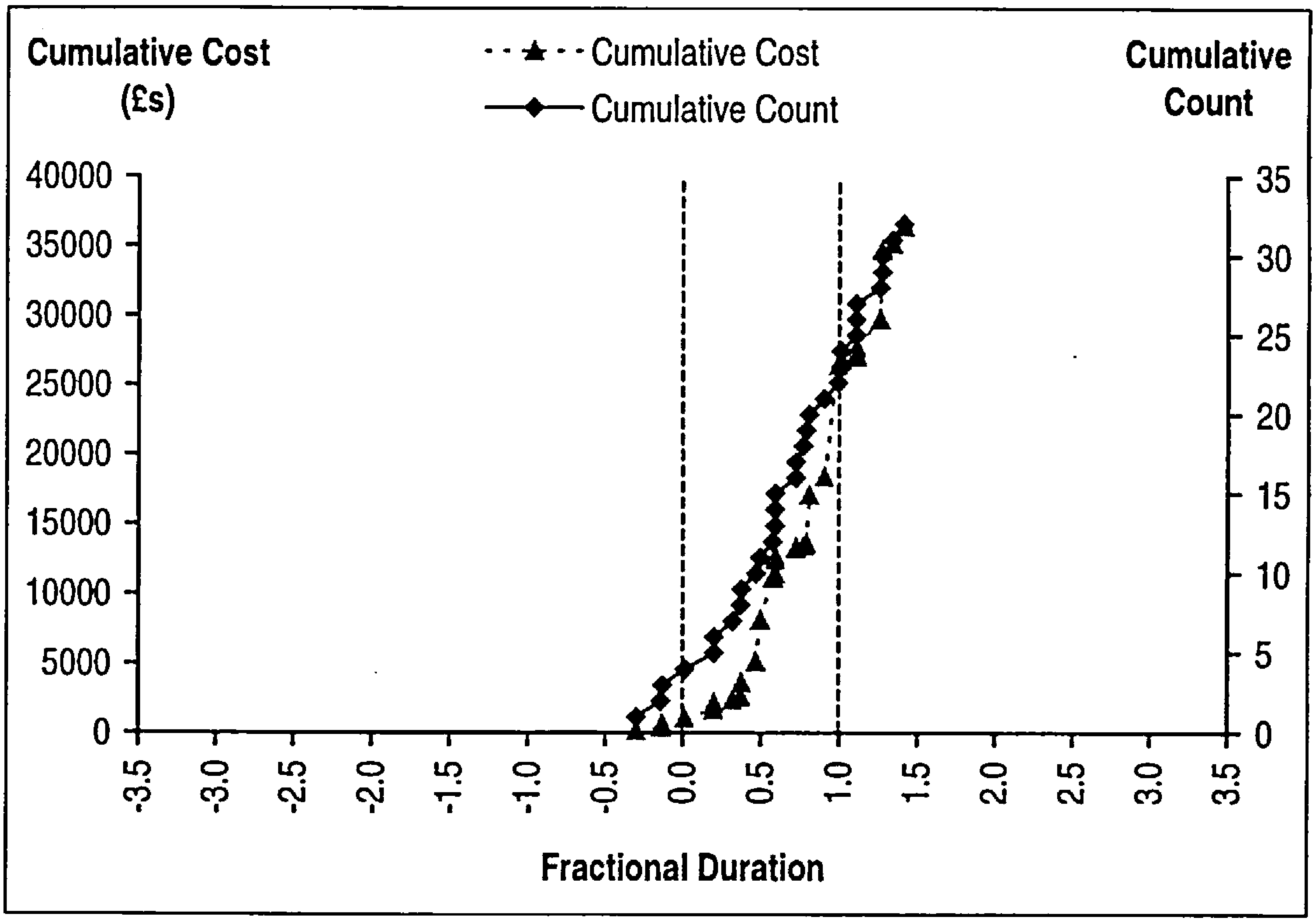


Figure B.12 - WP 5010: Blockwork/Partitions

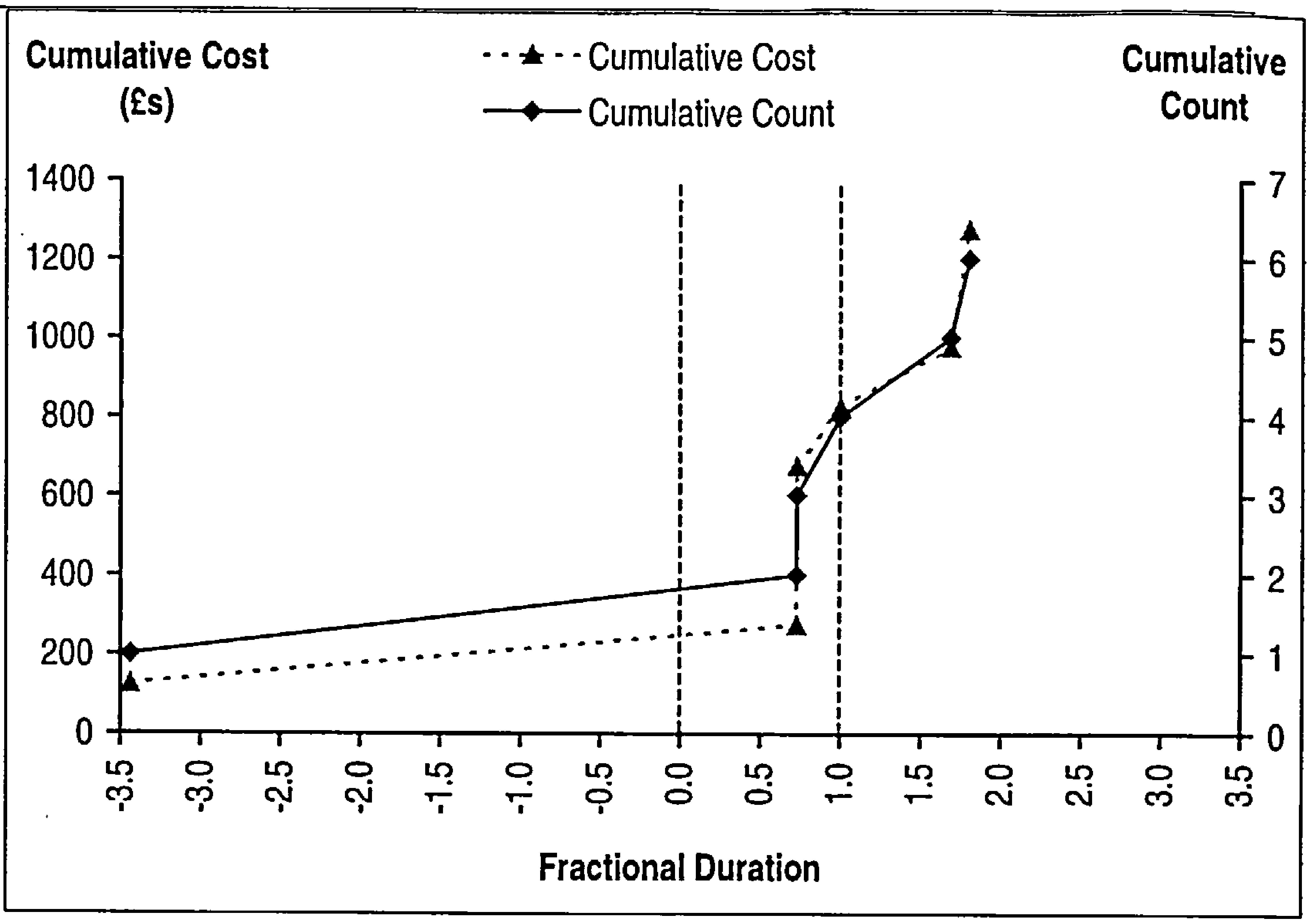


Figure B.13 - WP 5020: Suspended Ceilings

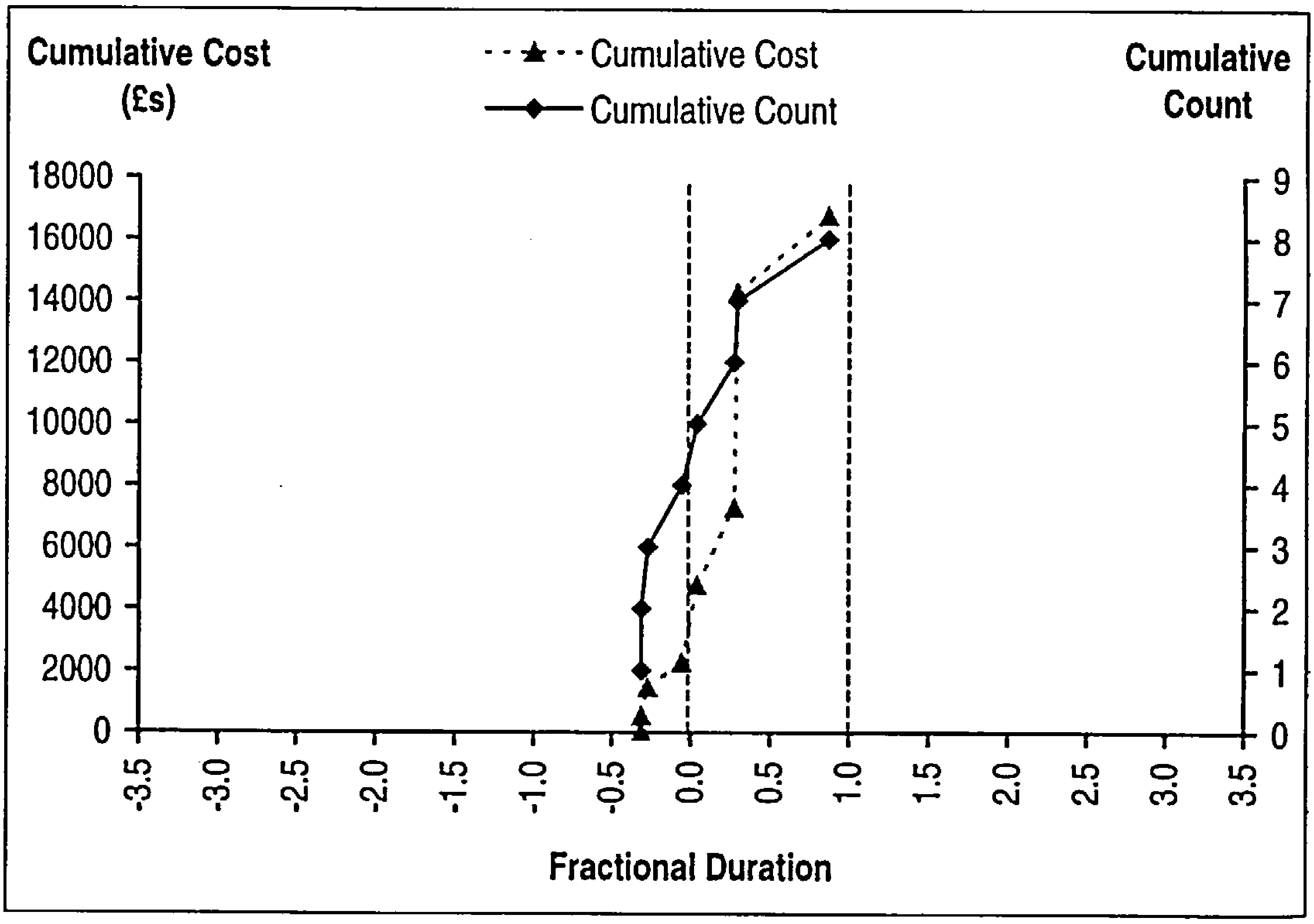


Figure B.14 – WP 5050: Architectural Metalwork

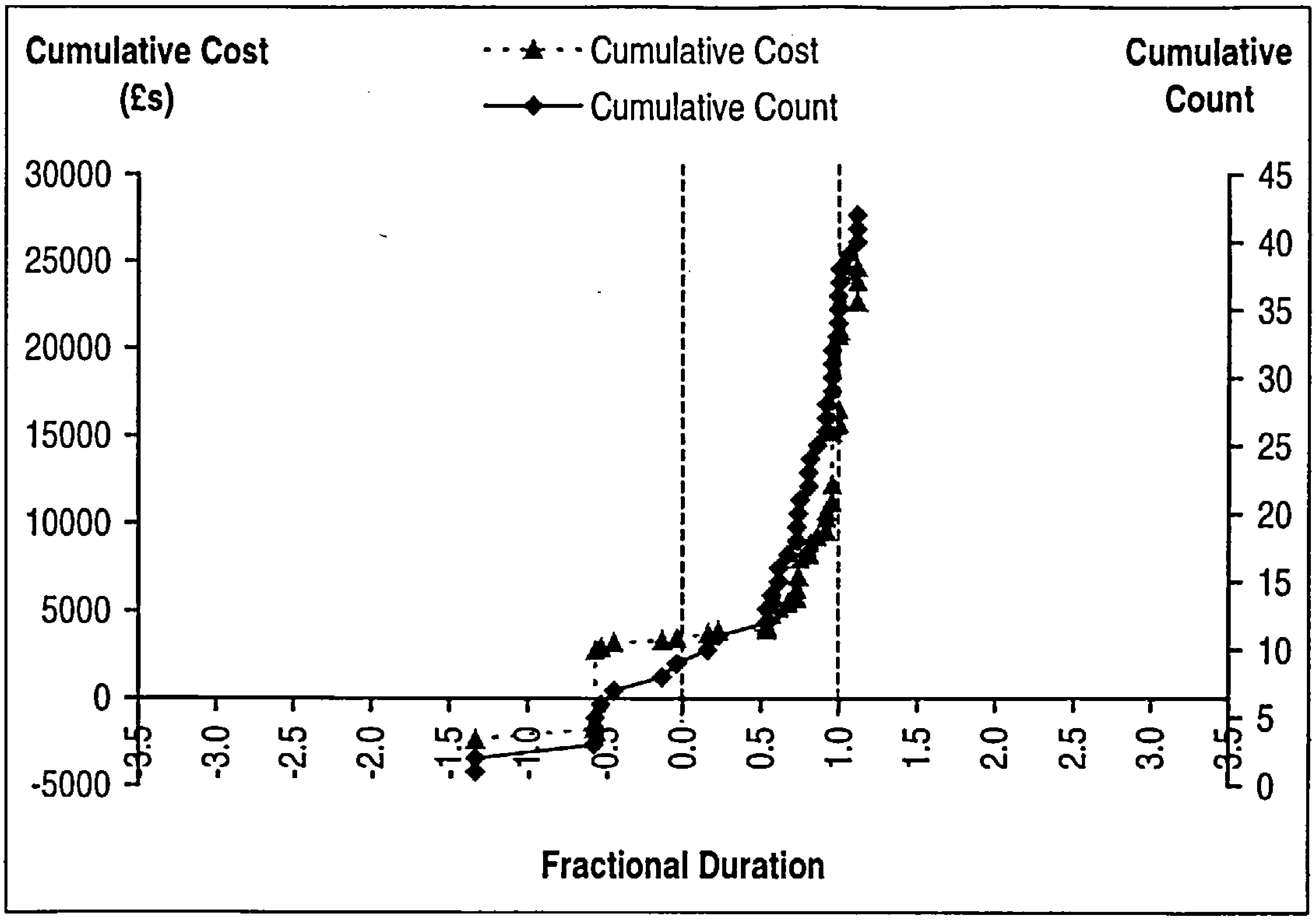


Figure B.15 – WP 5060: Furnishings Fit-out

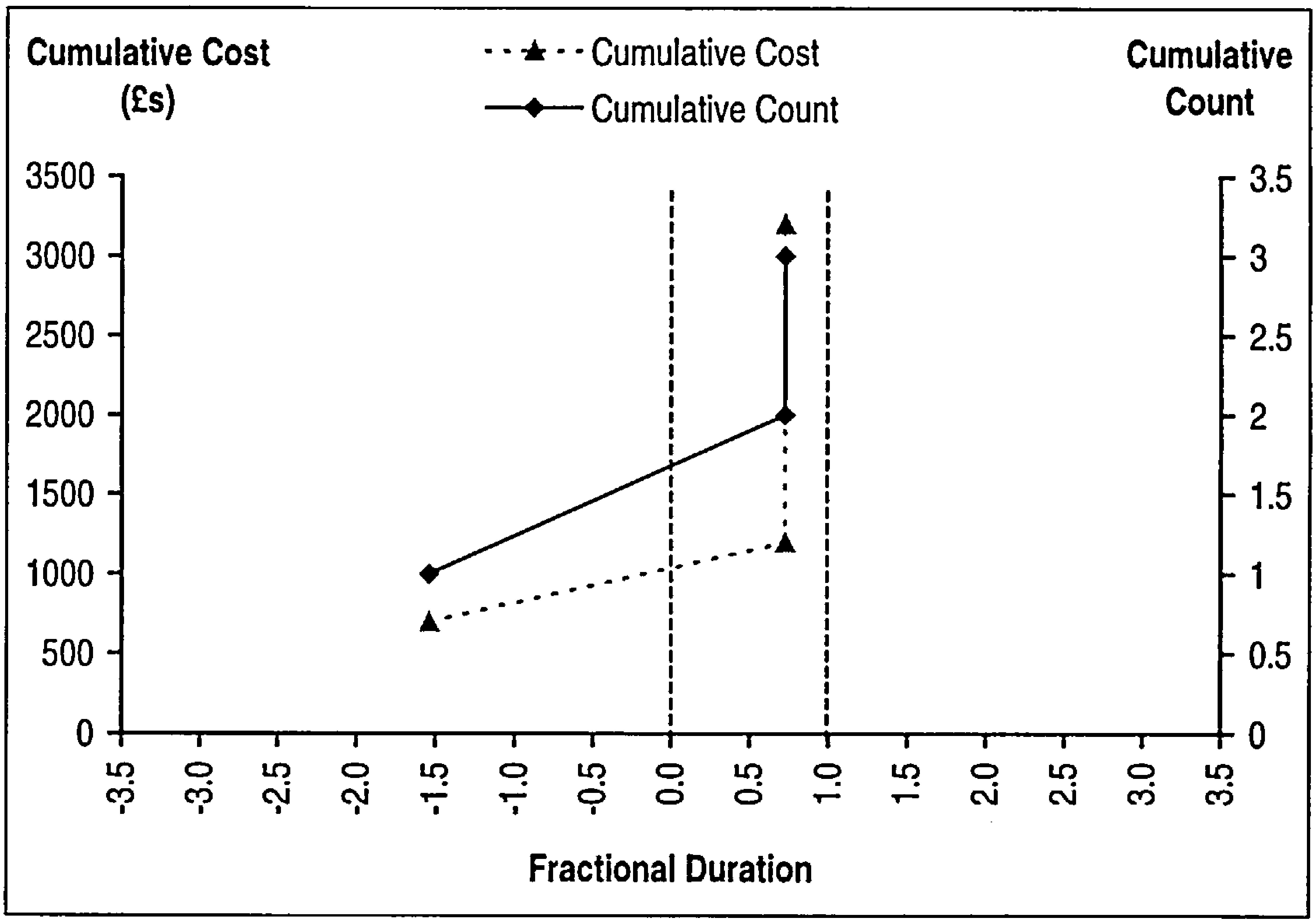


Figure B.16 – WP 5061: Carols and Shelving

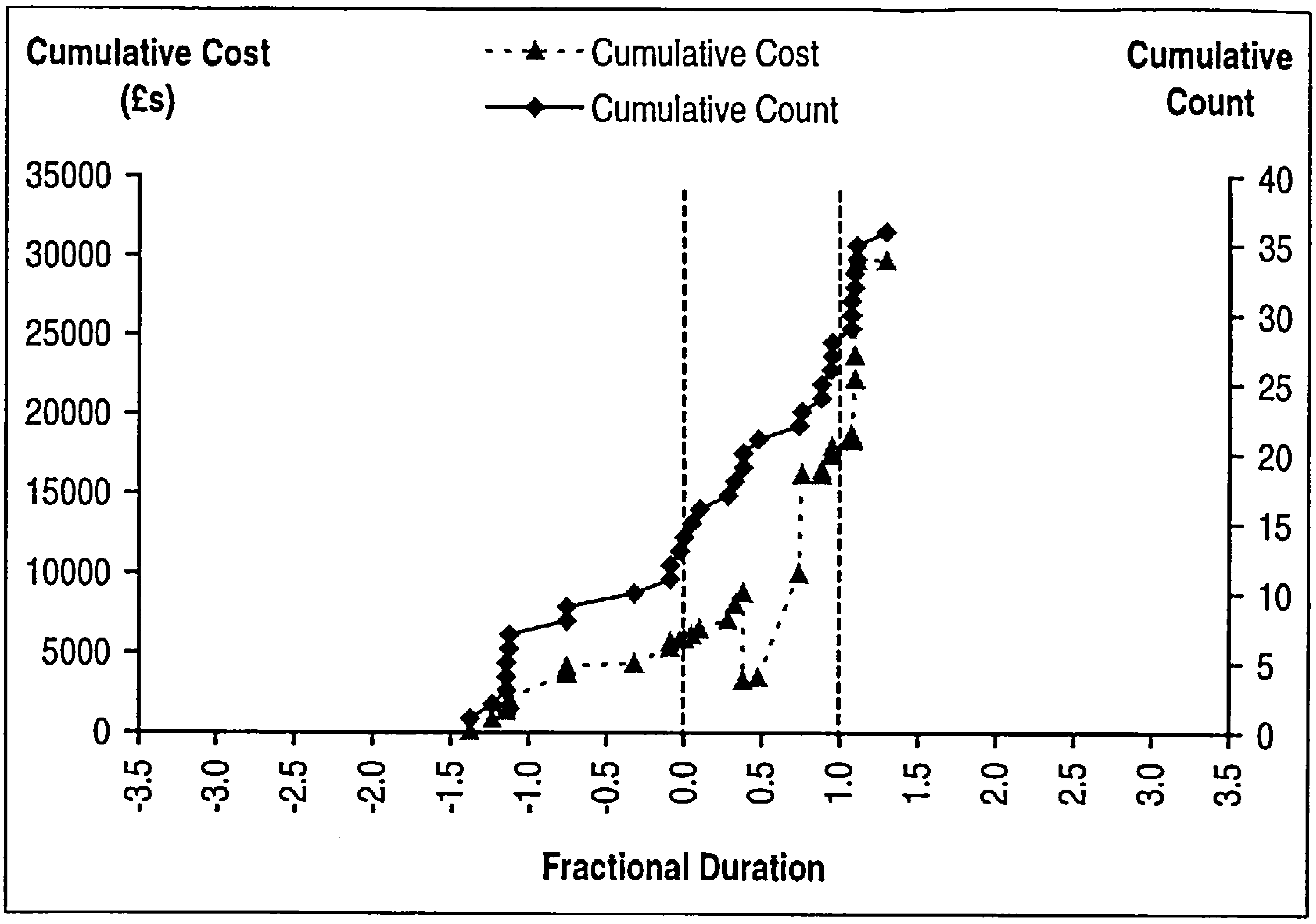


Figure B.17 – WP 6010: Electrical Services

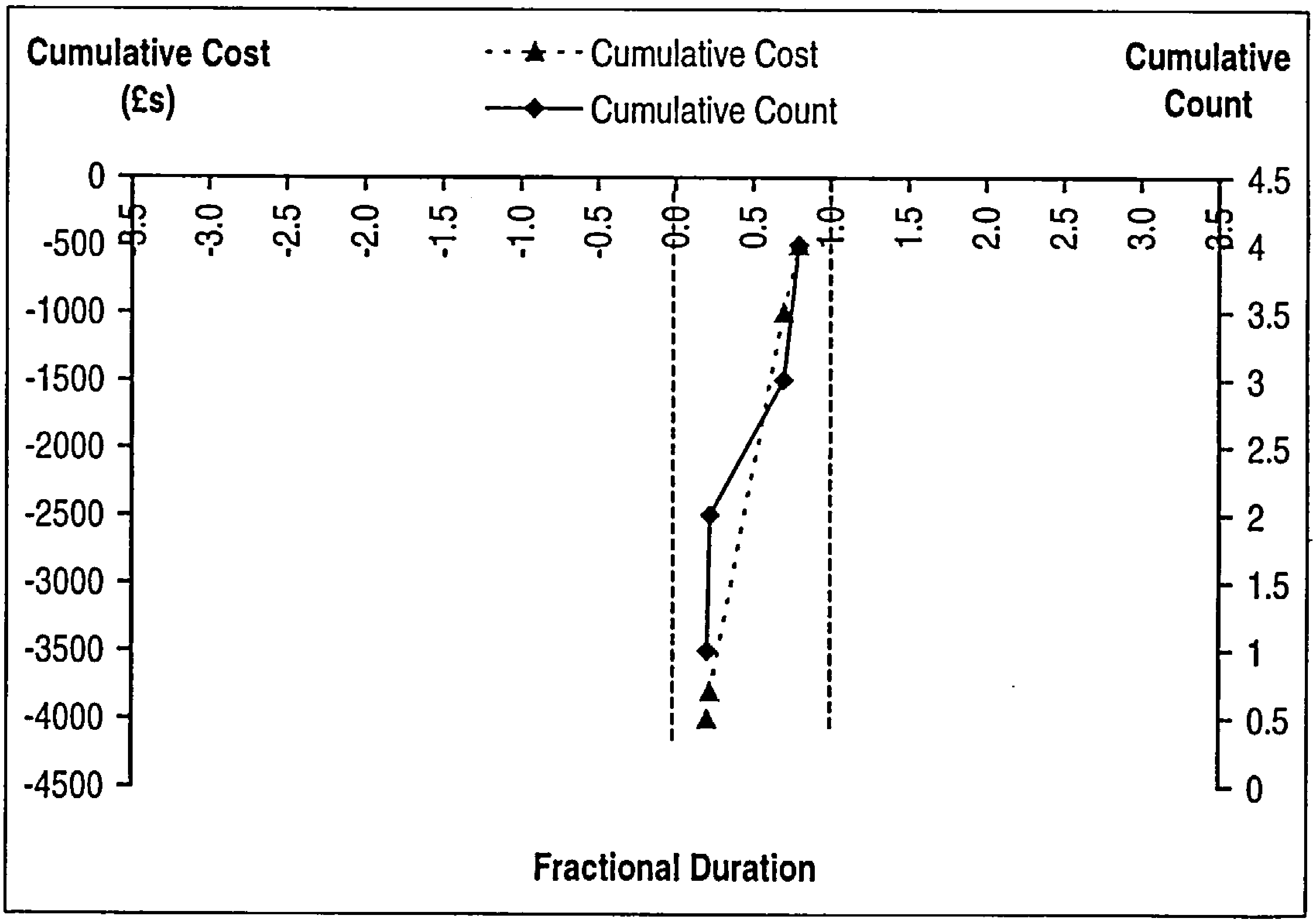


Figure B.18 – WP 6020: IT/Communications

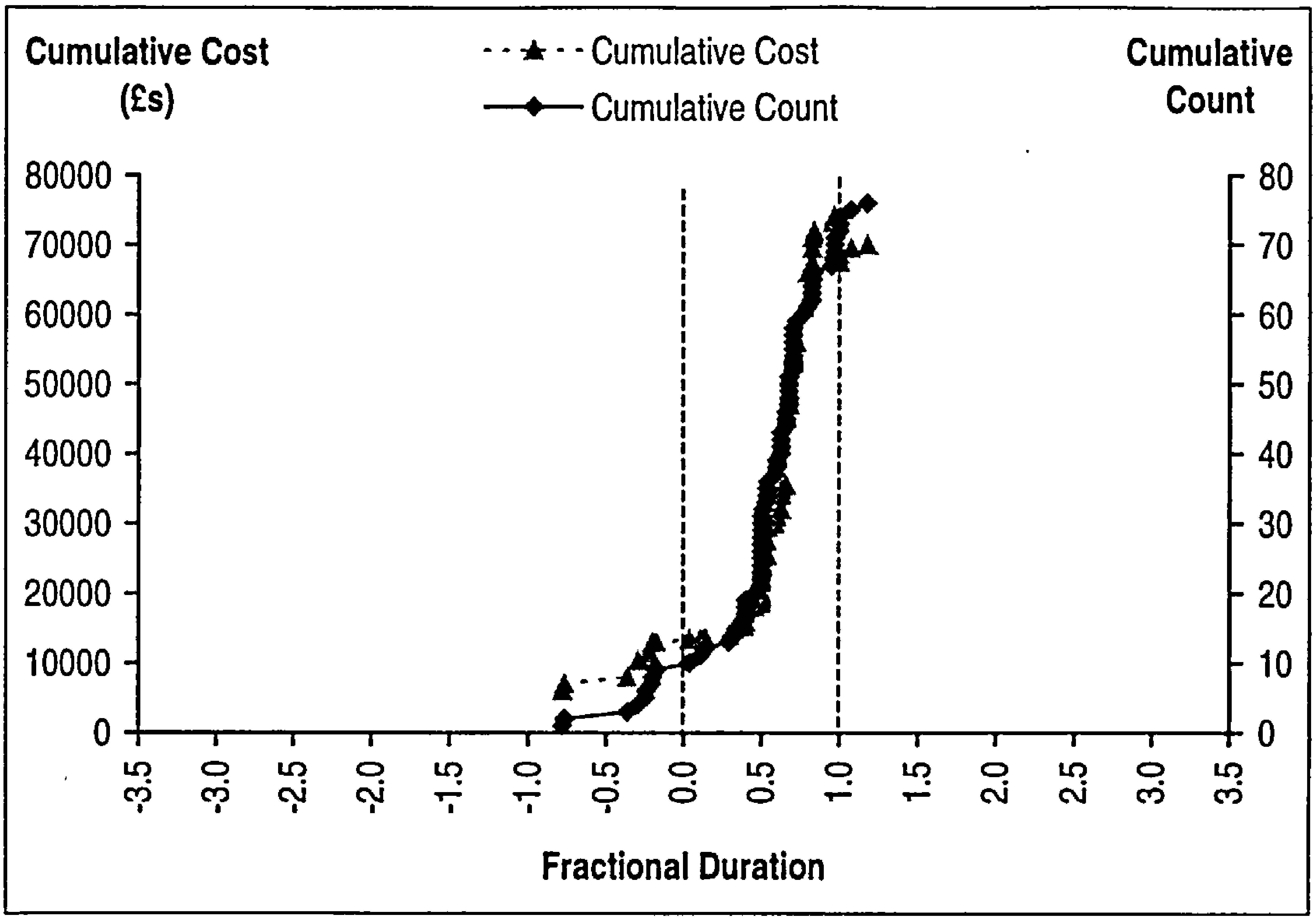


Figure B.19 – WP 7010: Mechanical Services

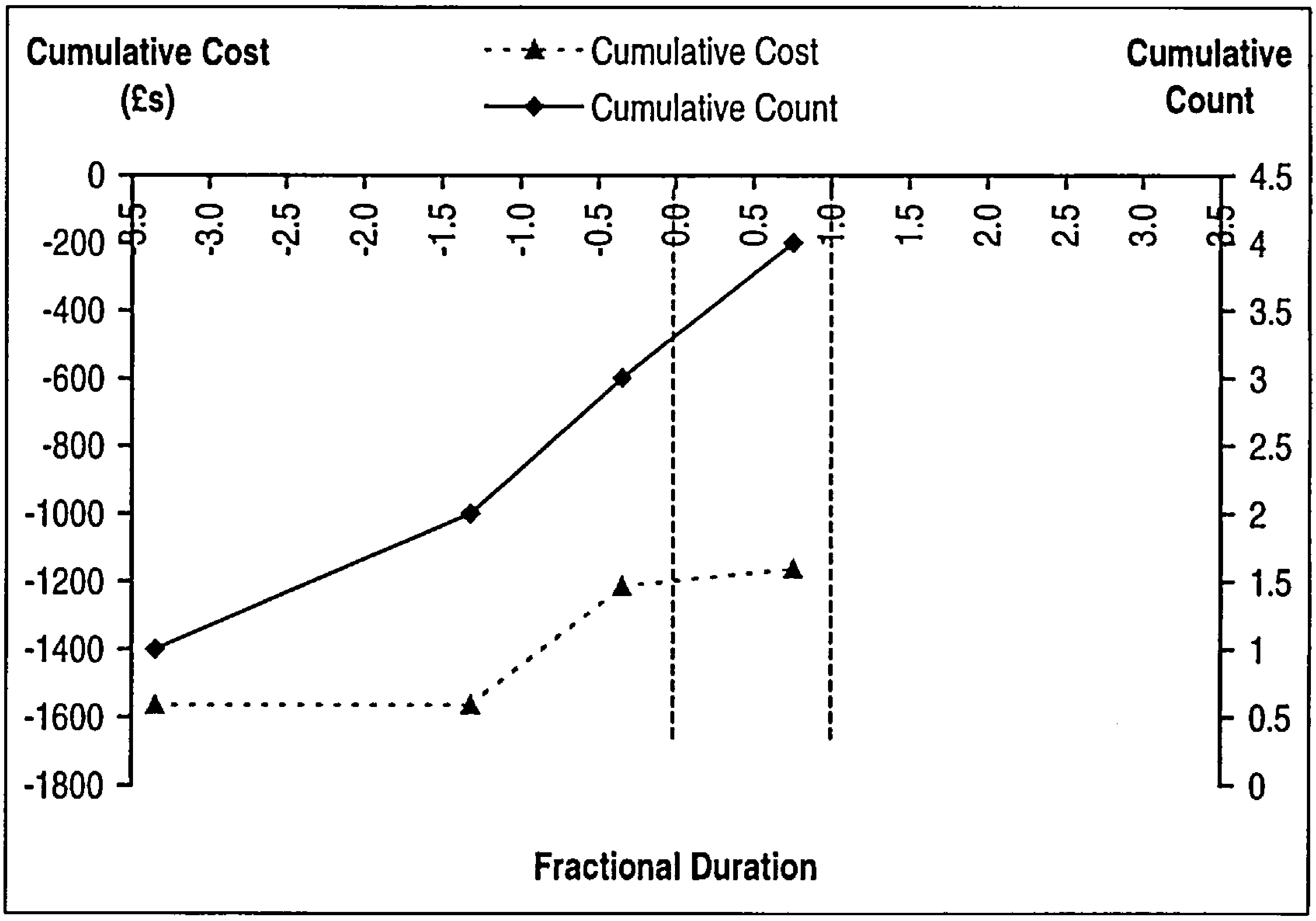


Figure B.20 – WP8010: Lifts

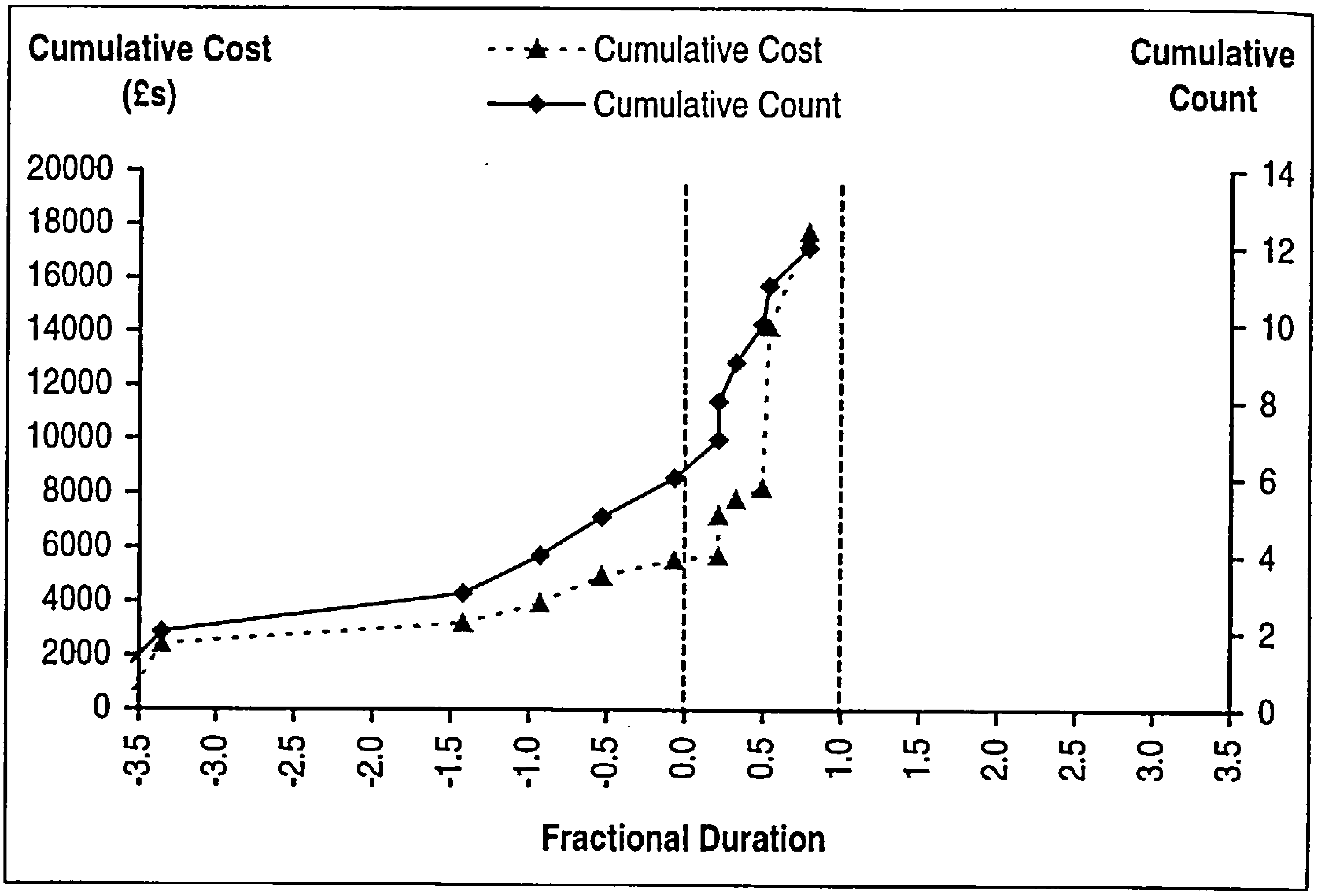


Figure B.21 – WP 9010 – Landscaping/Drainage

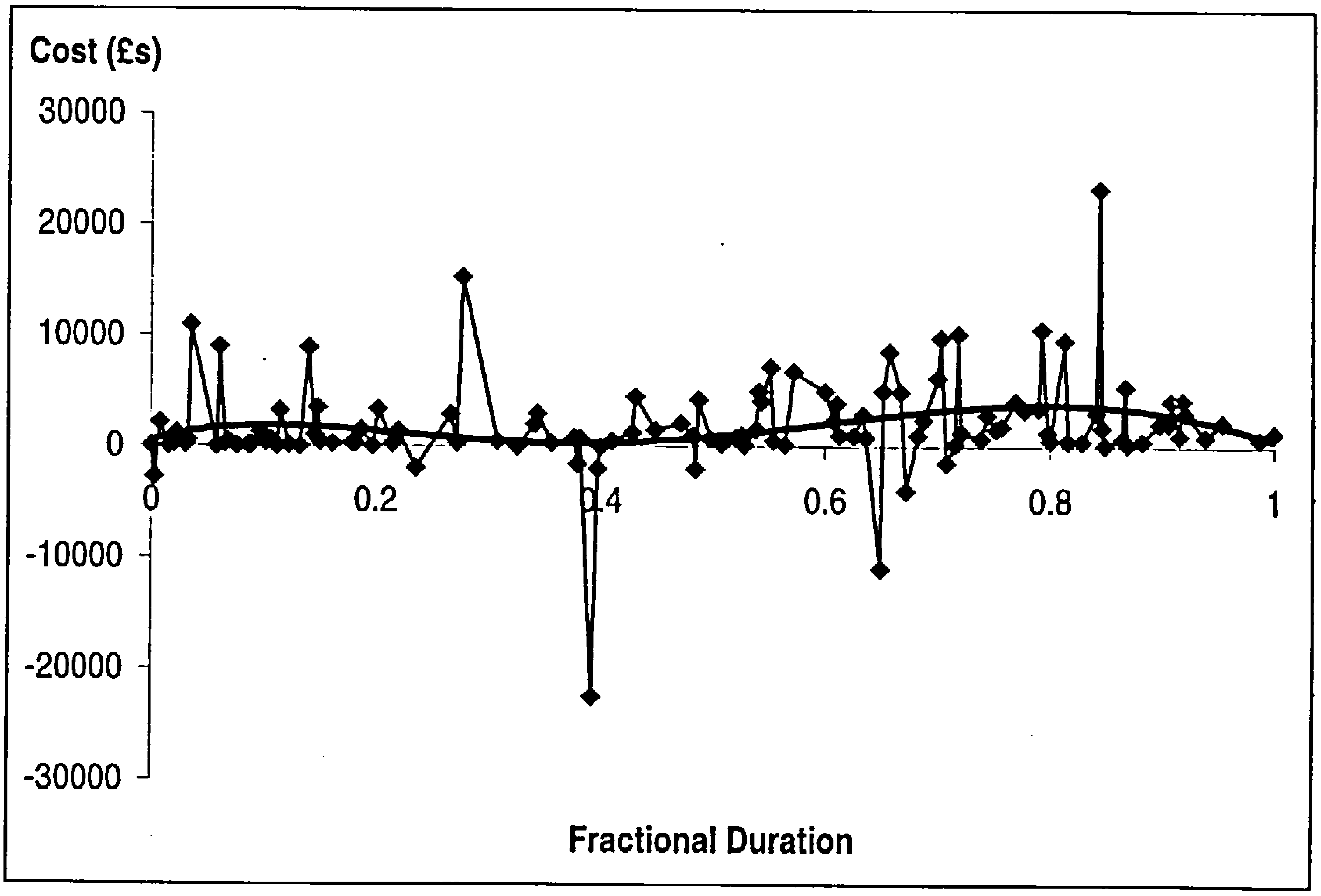


Figure B.22 – Change Order Request Costs: All Change Orders Over the Entire Period When Change Orders Were Used

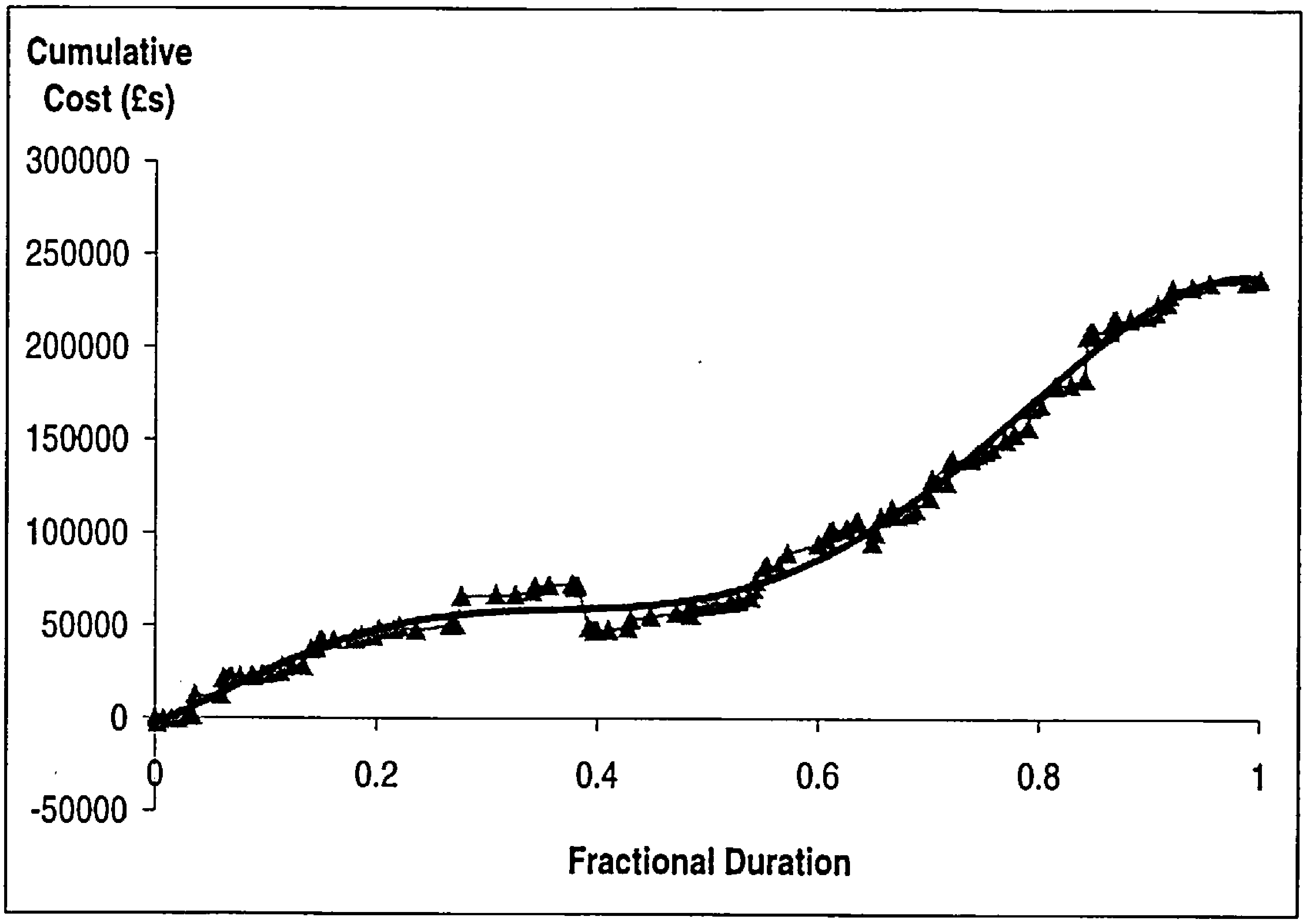


Figure B.23 – Cumulative Cost of All Change Orders Over the Entire Period When Change Orders Were Used

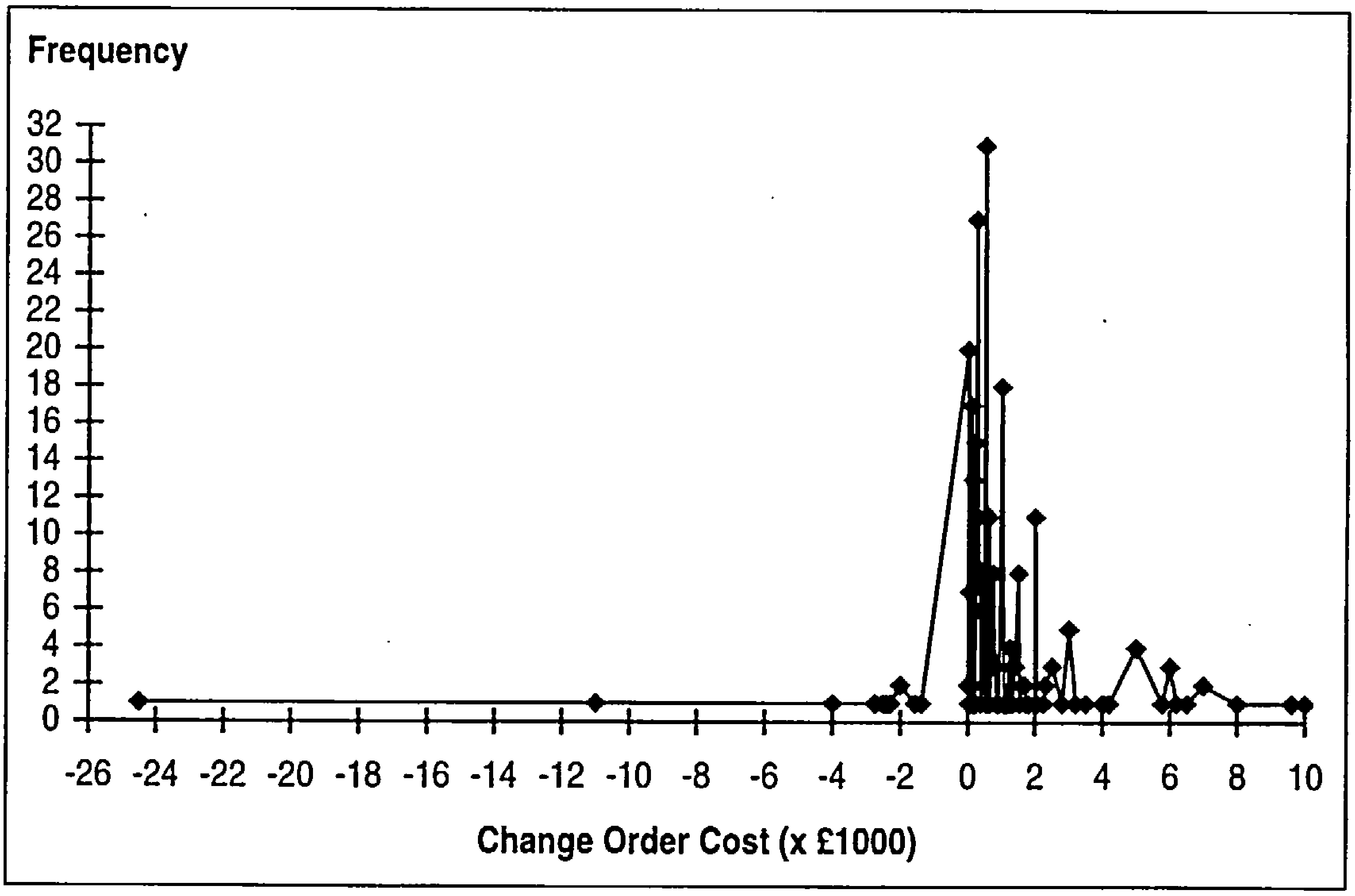


Figure B.24 – Distribution of Change Order Costs: Raw Data

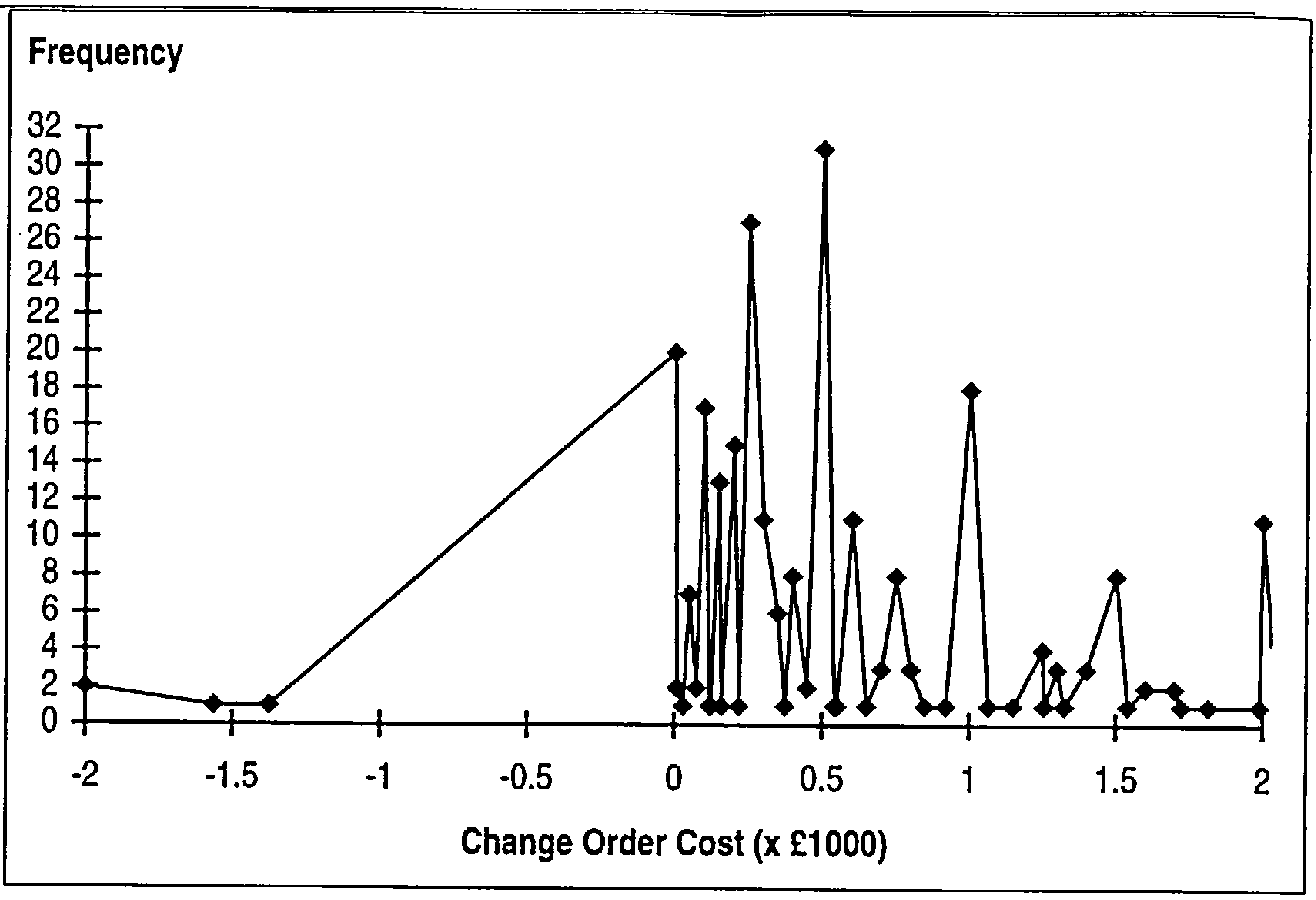


Figure B.24b – Distribution of Change Order Costs: Raw Data (-£2000 to £2000)

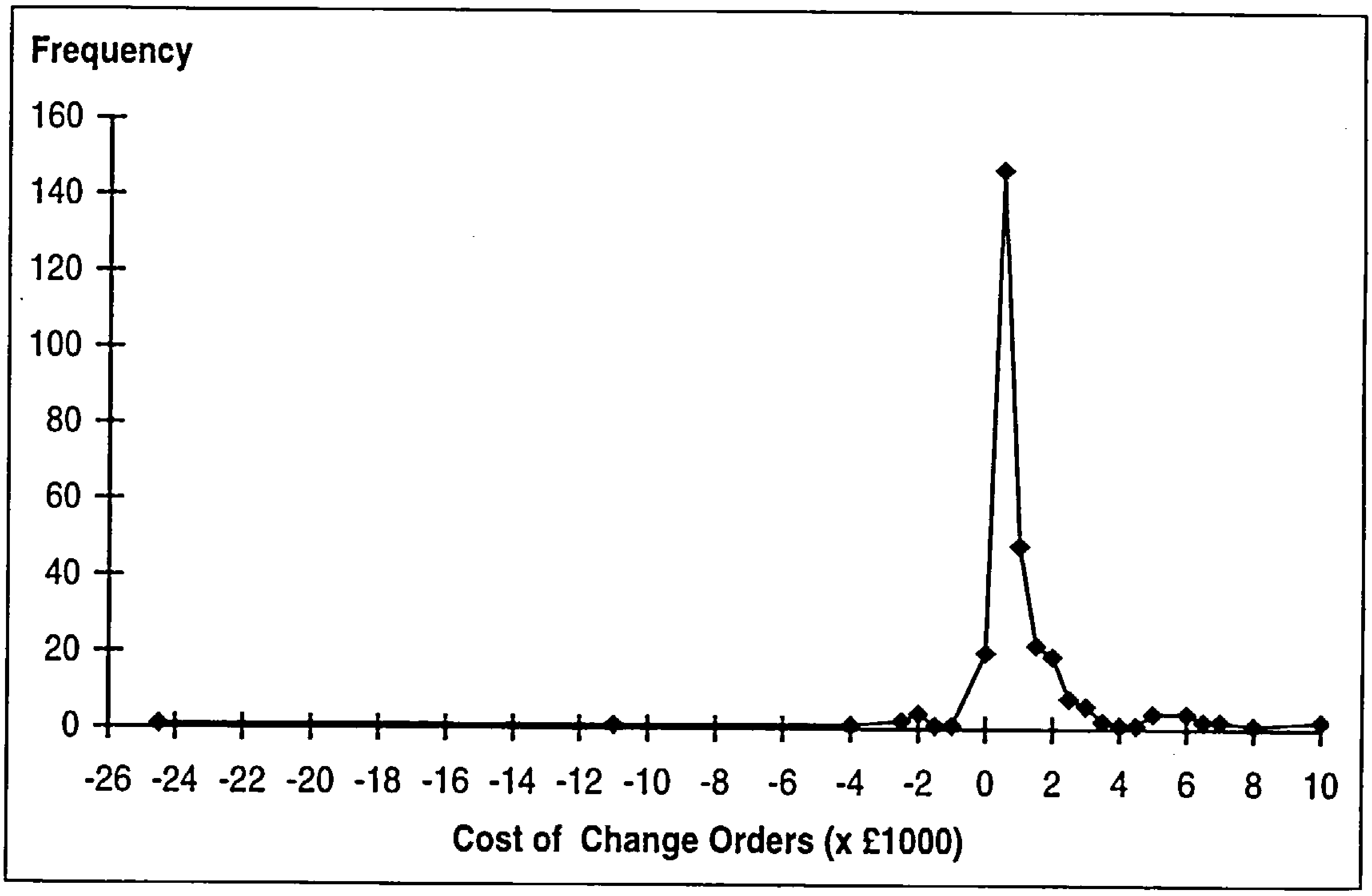


Figure B.25 – Distribution of Change Order Costs: Cost Class Intervals of £500

APPENDIX C

List of Figures

Figure C.1 – Change Order Costs: Work Package & Reason (WP 10010-1 – WP 4035-2) 3
Figure C.2 – Change Order Costs: Work Package & Reason (WP 4035-3 – WP 9020) 3
Figure C.3 – Fractional Cost of Change Orders for Each Work Package (WP 10010-1 – WP 4035-2) 4
Figure C.4 – Fractional Cost of Change Orders for Each Work Package (WP 4035-3 – WP 9020) 4
Figure C.5 – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2) 5
Figure C.5 – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2) 5
Figure C.7 – Change Order Costs Associated With Each Reason Category 6
Figure C.8 – Number of Change Orders Specifying Each Reason Category 6
Figure C.9 – WP 3010-1: Substructure 7
Figure C.10 – WP 3010-2: Substructure 7
Figure C.11 – WP 4010: Structural Steel Work 8
Figure C.12 – WP 4020-2: Office Roof 8
Figure C.13 – WP 4025: Cladding/Covering 9
Figure C.14 – WP 4030: Curtain Walling 9
Figure C.15 – WP 4035-1: Doors and Ironmongery 10
Figure C.16 – WP 4035-2: Metal Doors/Hatches 10
Figure C.17 – WP 4035-3: Balustrading 11
Figure C.18 – WP 4040-1: Windows and Louvres 11
Figure C.19 – WP 4040-2: Solar Screens 12
Figure C.20 – WP 5010: Brickwork/Blockwork and Plaster 12
Figure C.21 – WP 5020: Ceiling Finishes 13

Figure C.22 – WP 5060 Fittings and Furnishings *13*
Figure C.23 – WP 6010-1: Building Services – Electrical *14*
Figure C.24 – WP 7010-1: Building Services - Mechanical *14*
Figure C.25 – WP 7010-2: Building Services - Mechanical *15*
Figure C.26 – WP 9010: External Works *15*
Figure C.27 – WP 9020: Site Works *16*
Figure C.28 – WP 10040: Tenant Fit-out *16*
Figure C.29 – Change Order Request Costs: All Change Orders Over the Entire Period When Change Orders Were Used *17*
Figure C.30 – Cumulative Cost of All Change Orders Over the Entire Period When Change Orders Were Used *17*
Figure C.31 – Change Order Cost Distribution: Raw Data *18*
Figure C.31b – Change Order Cost Distribution: Raw Data (-£2000 to £2000) *18*
Figure C.32 – Distribution of Change Order Costs: Cost Class Intervals of £500 .... *19*

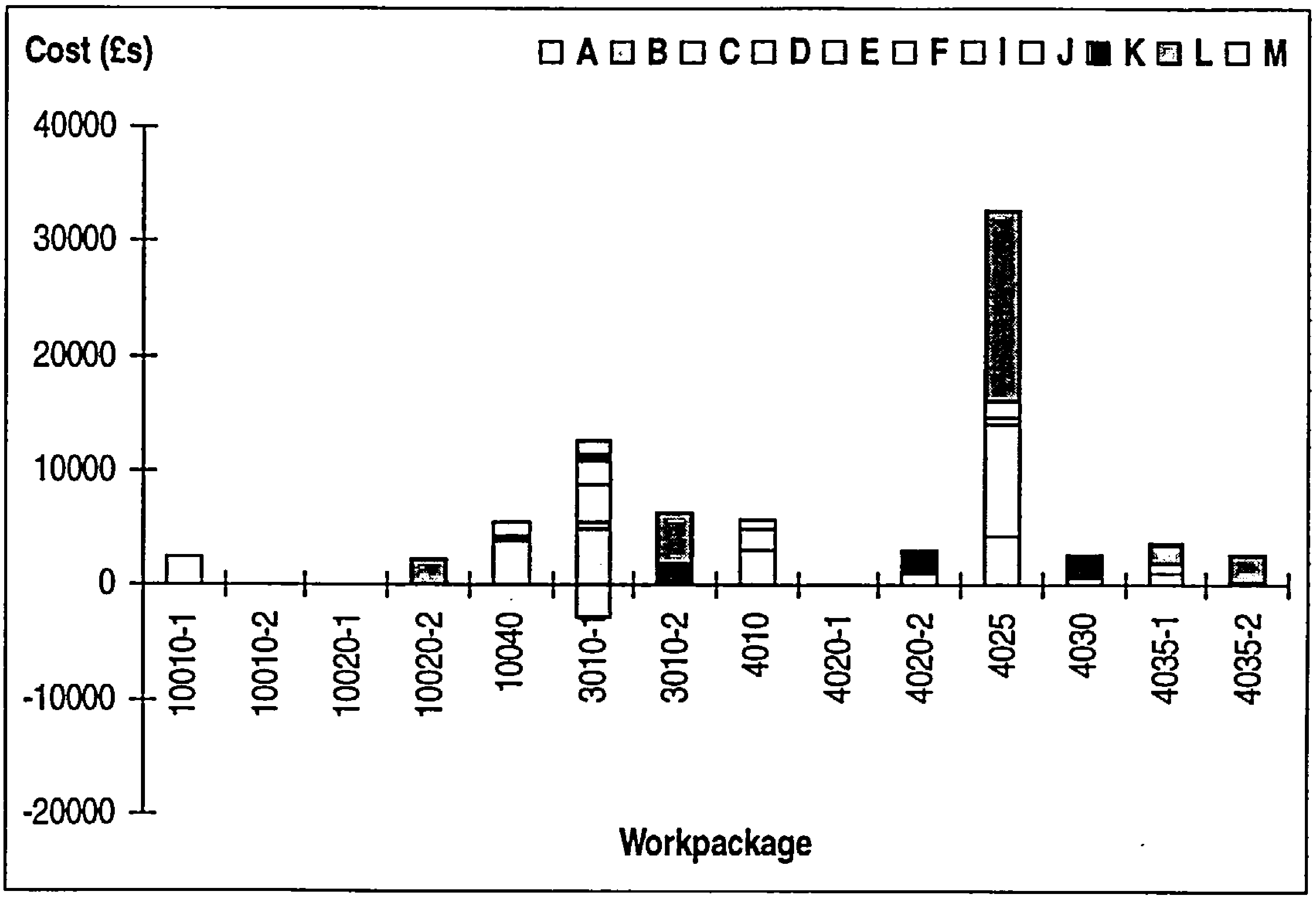


Figure C.1 – Change Order Costs: Work Package & Reason (WP 10010-1 – WP 4035-2)

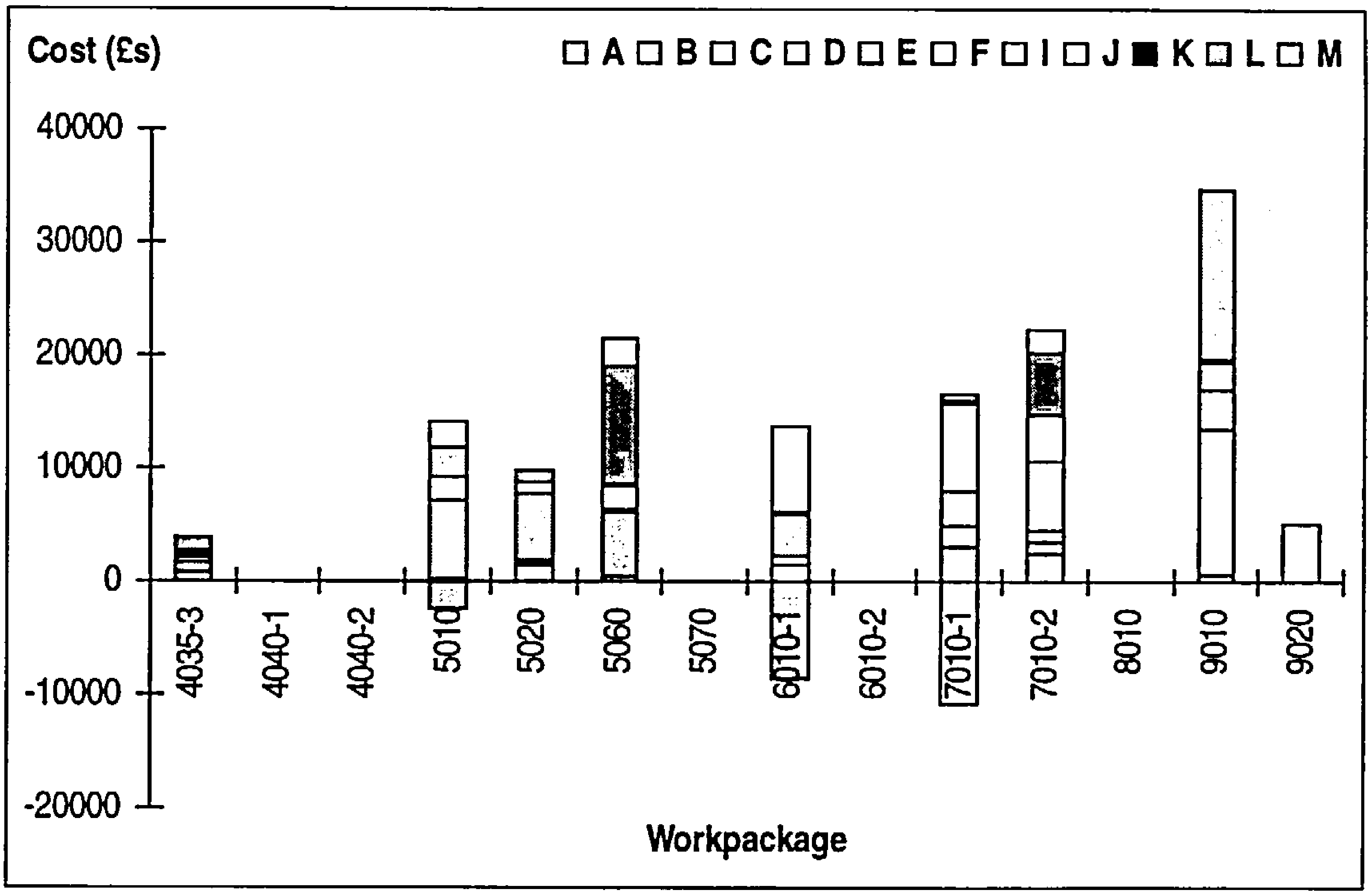


Figure C.2 – Change Order Costs: Work Package & Reason (WP 4035-3 – WP 9020)

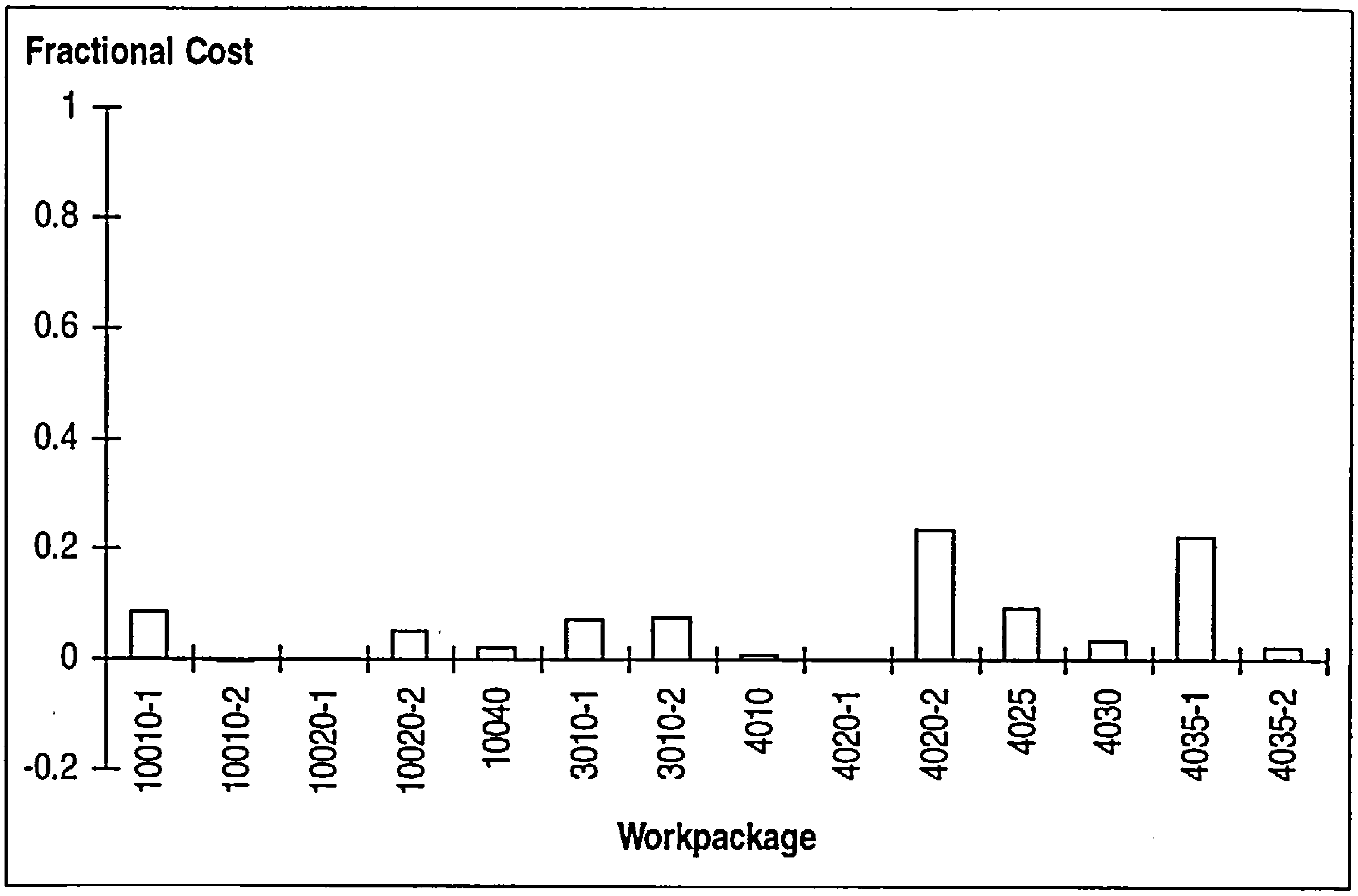


Figure C.3 – Fractional Cost of Change Orders for Each Work Package (WP 10010-1 – WP 4035-2)

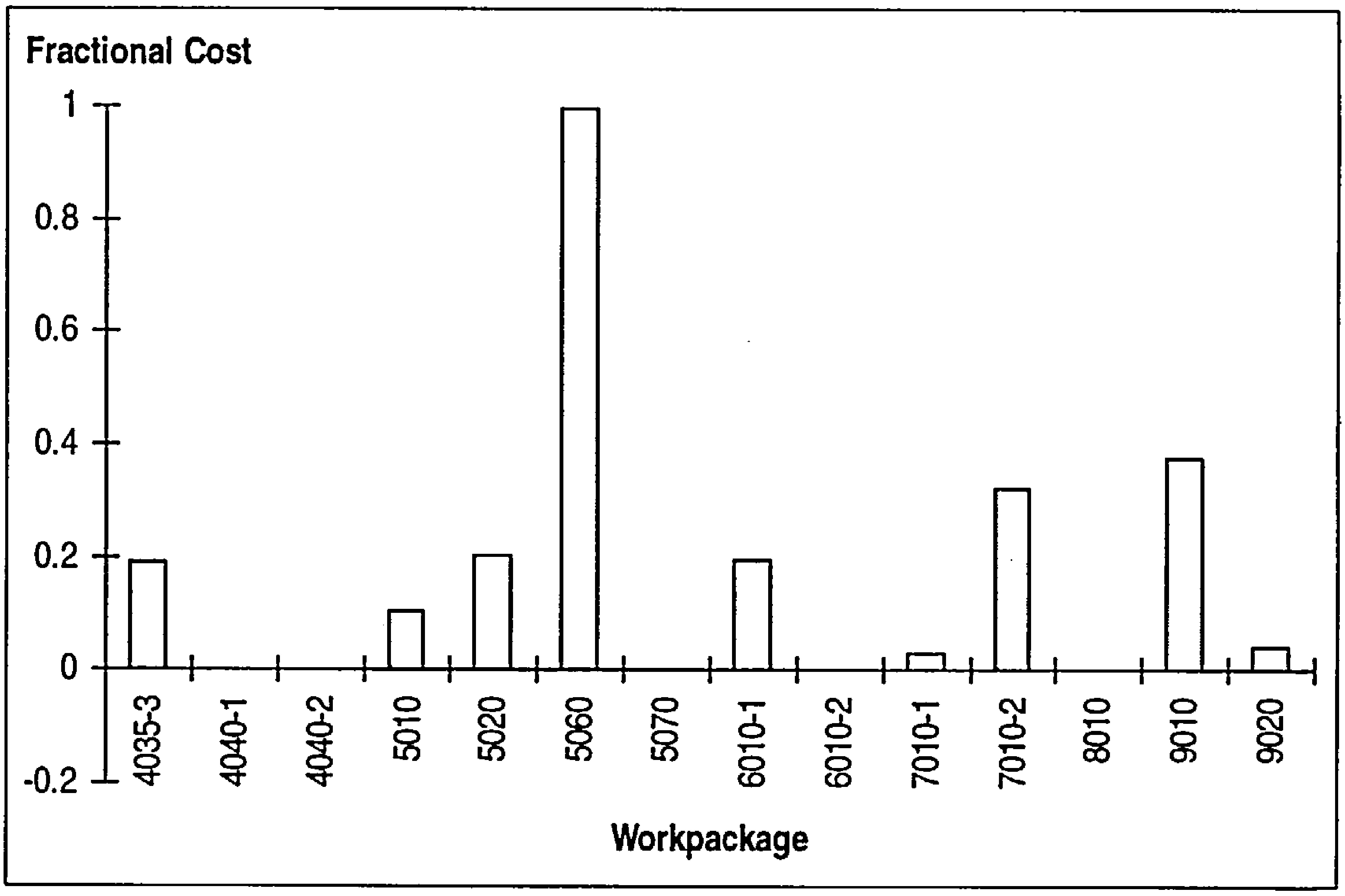


Figure C.4 – Fractional Cost of Change Orders for Each Work Package (WP 4035-3 – WP 9020)

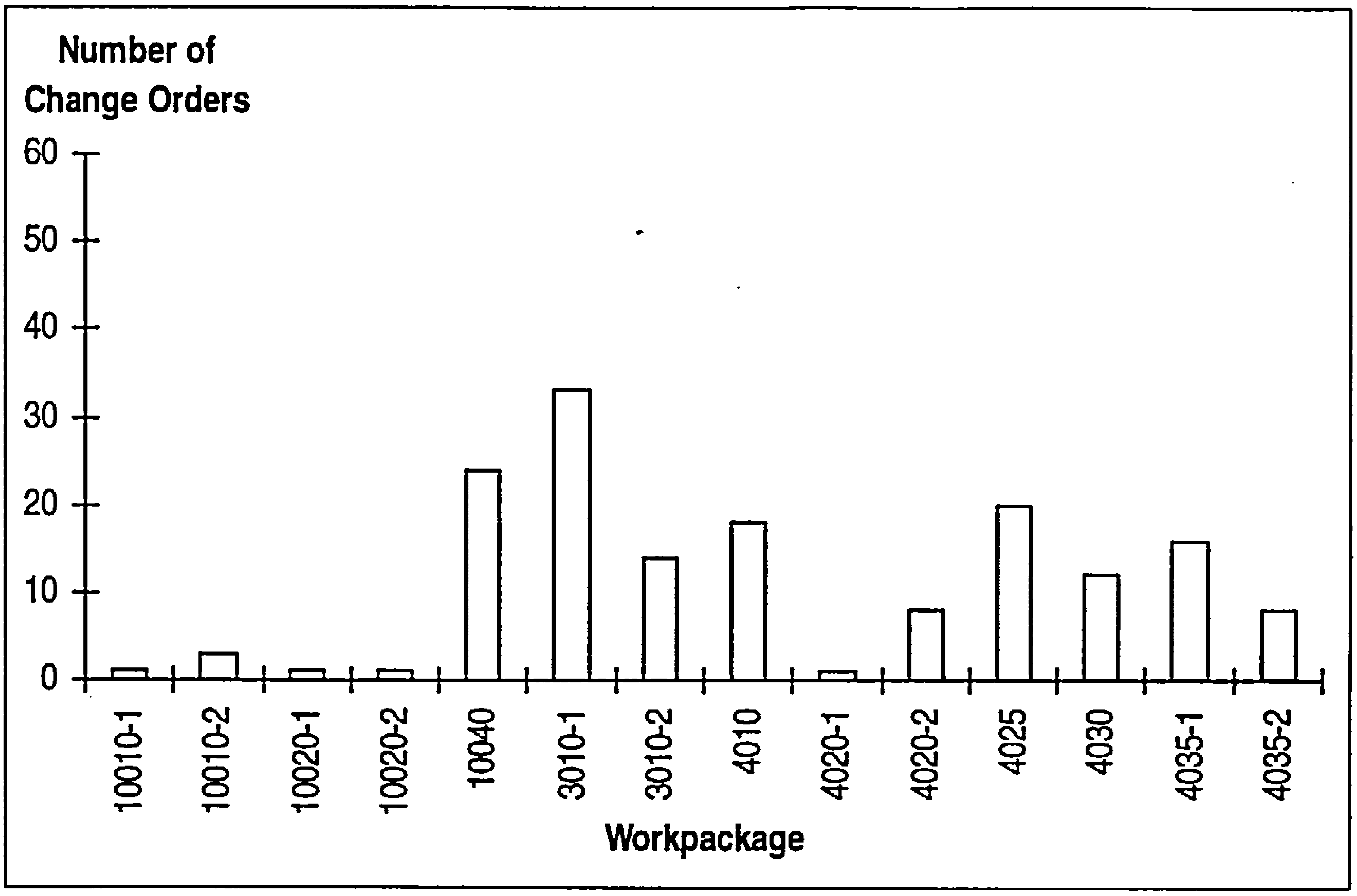


Figure C.5 – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2)

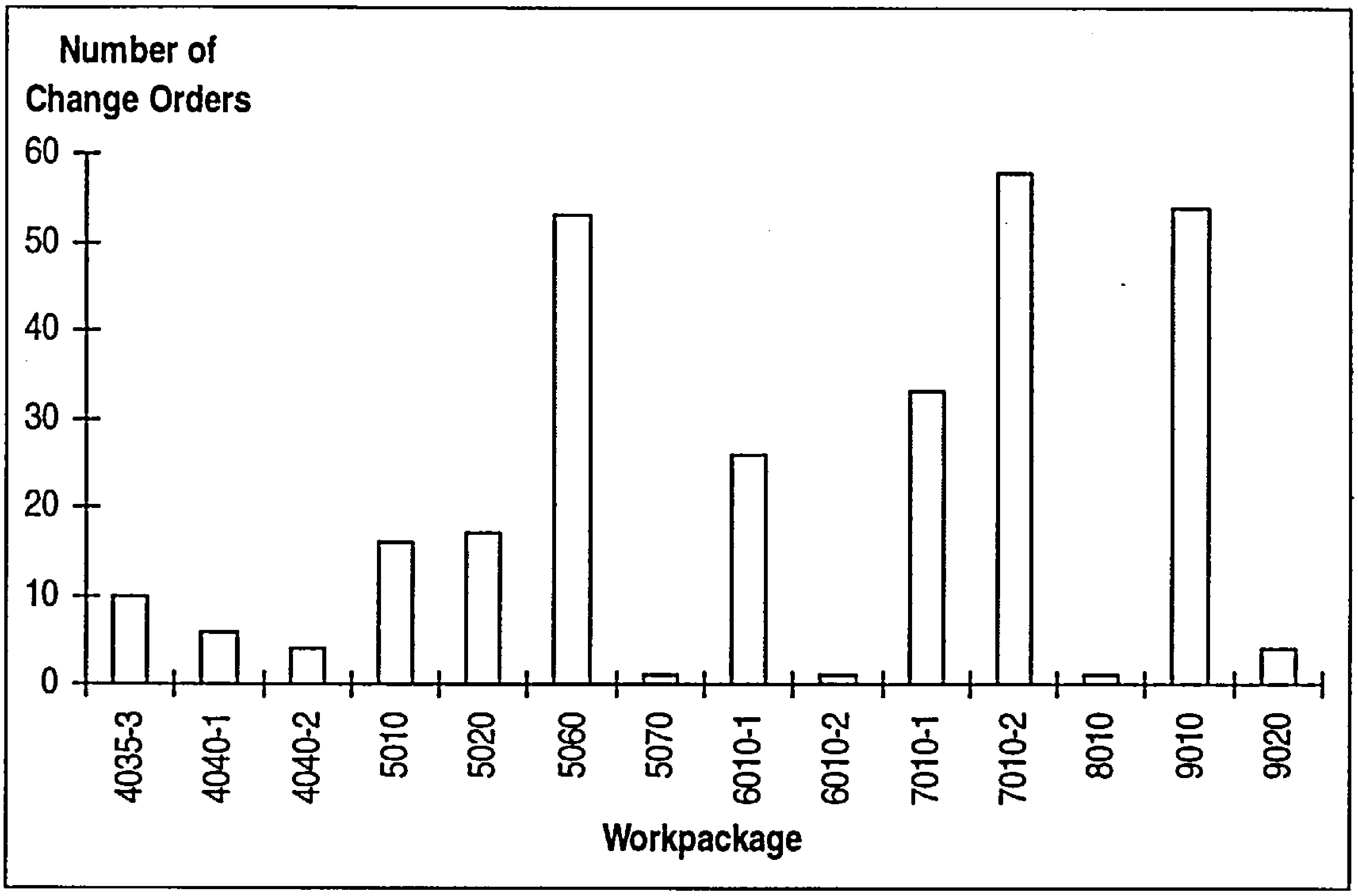


Figure C.5 – Number of Change Orders Affecting Each Work Package (WP 10010-1 – WP 4035-2)

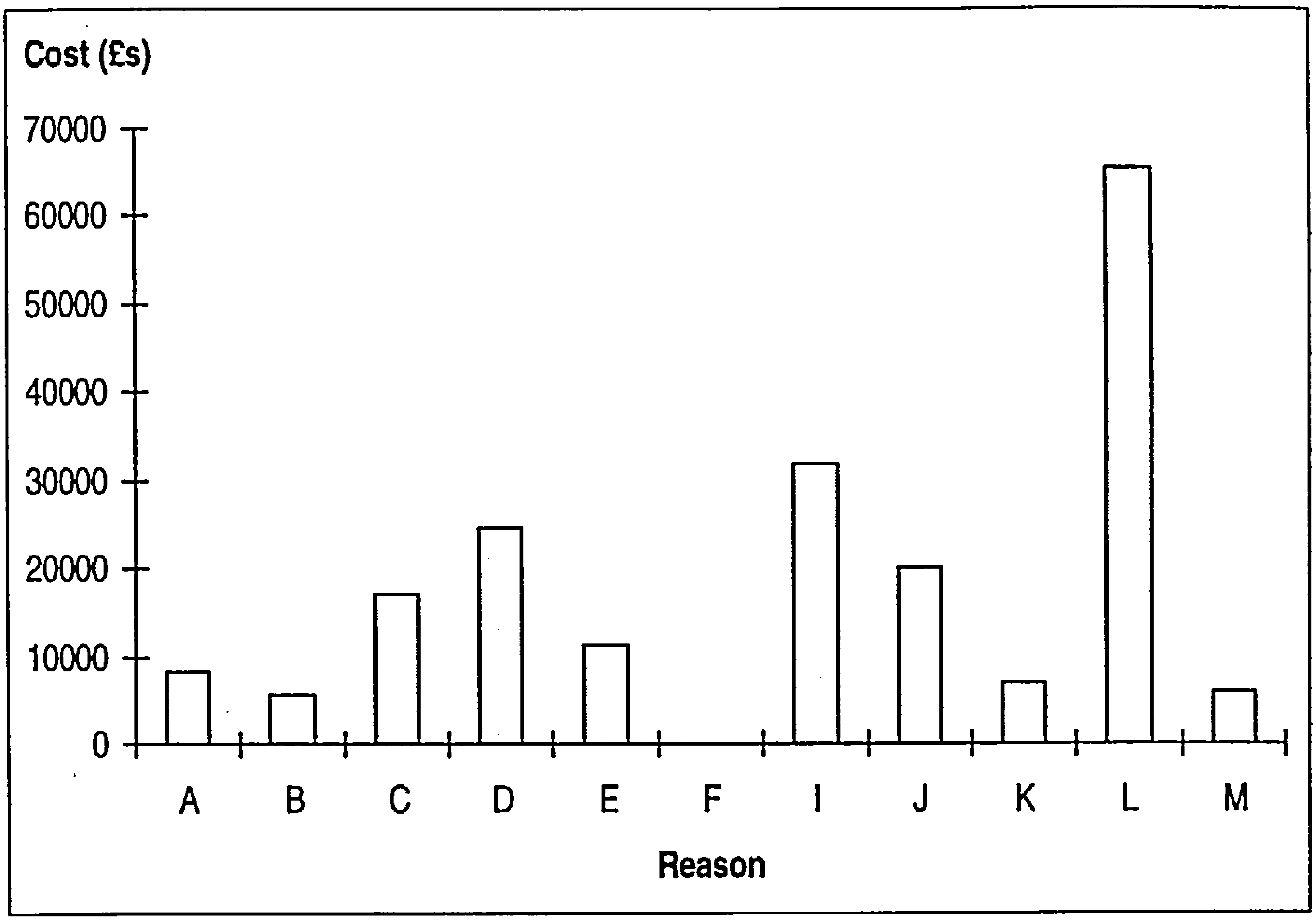


Figure C.7 – Change Order Costs Associated With Each Reason Category

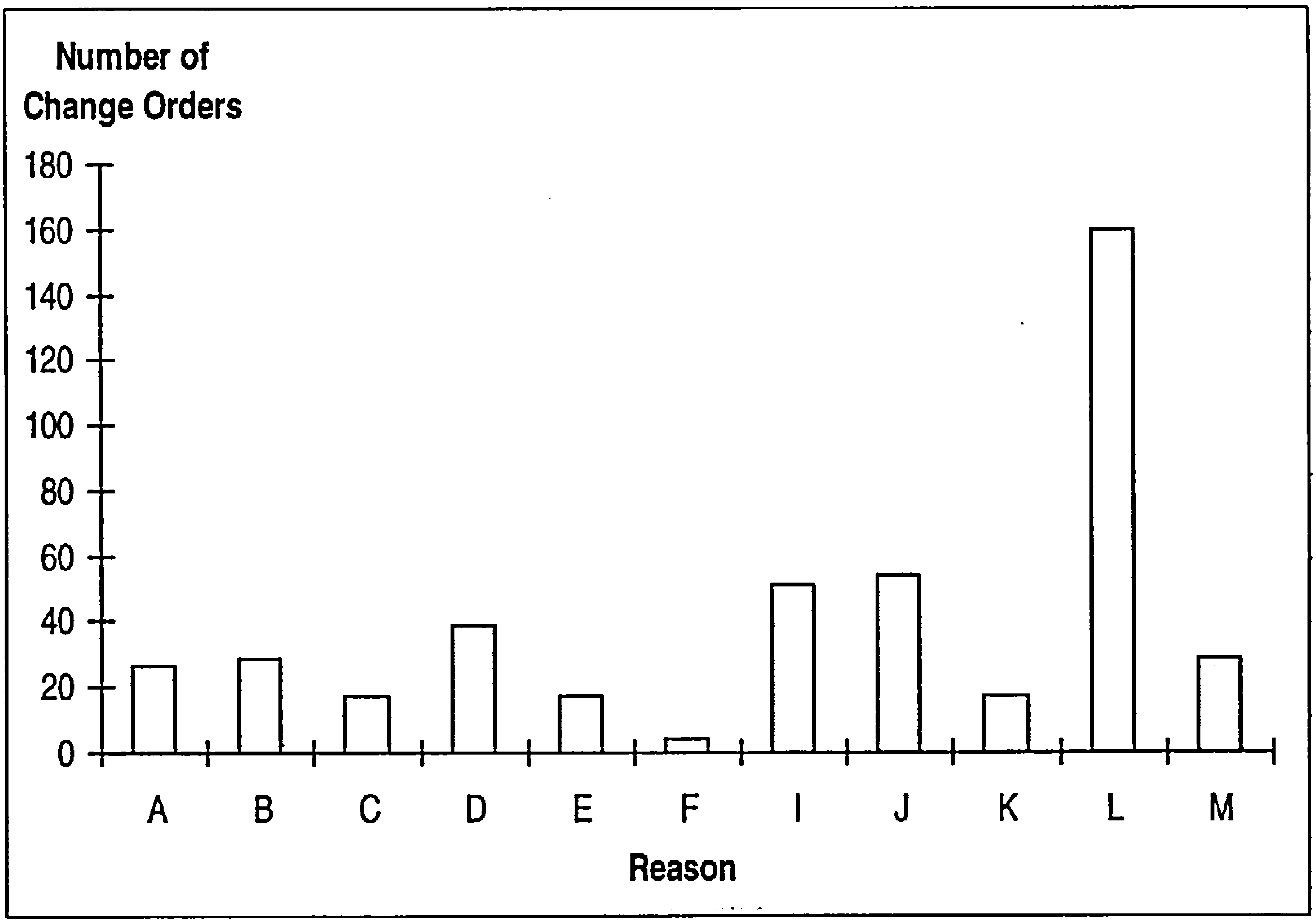


Figure C.8 – Number of Change Orders Specifying Each Reason Category

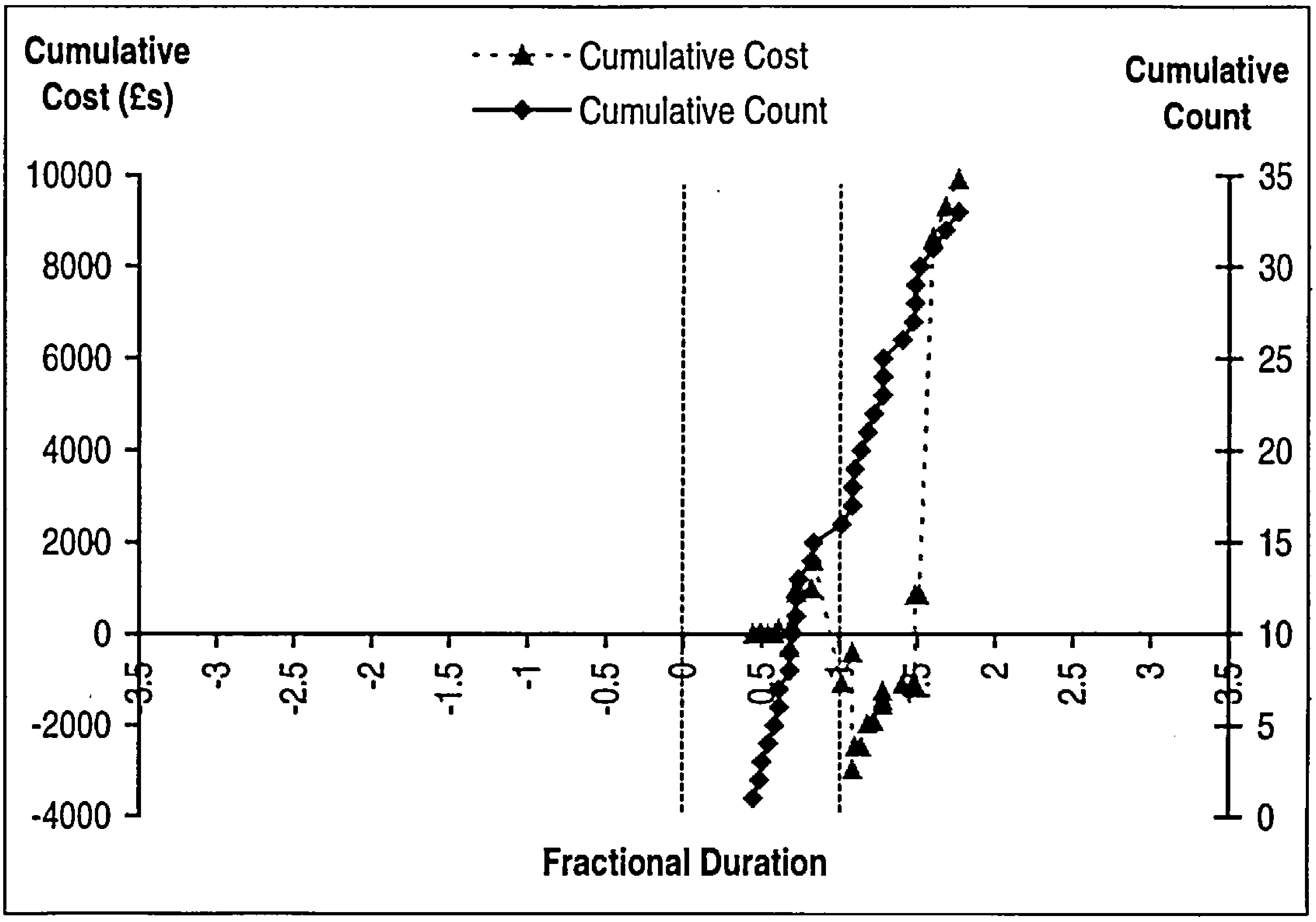


Figure C.9 – WP 3010-1: Substructure

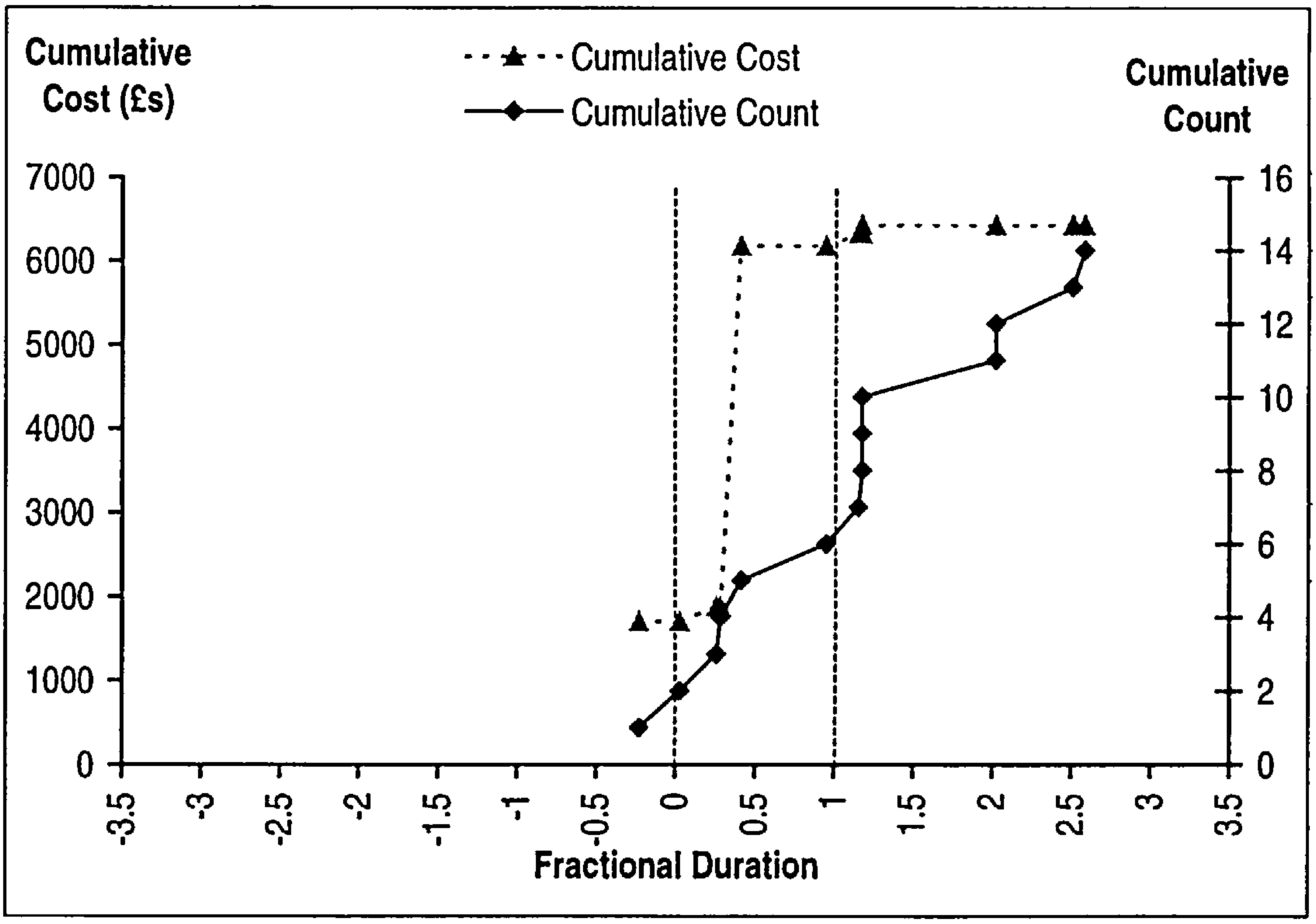


Figure C.10 – WP 3010-2: Substructure

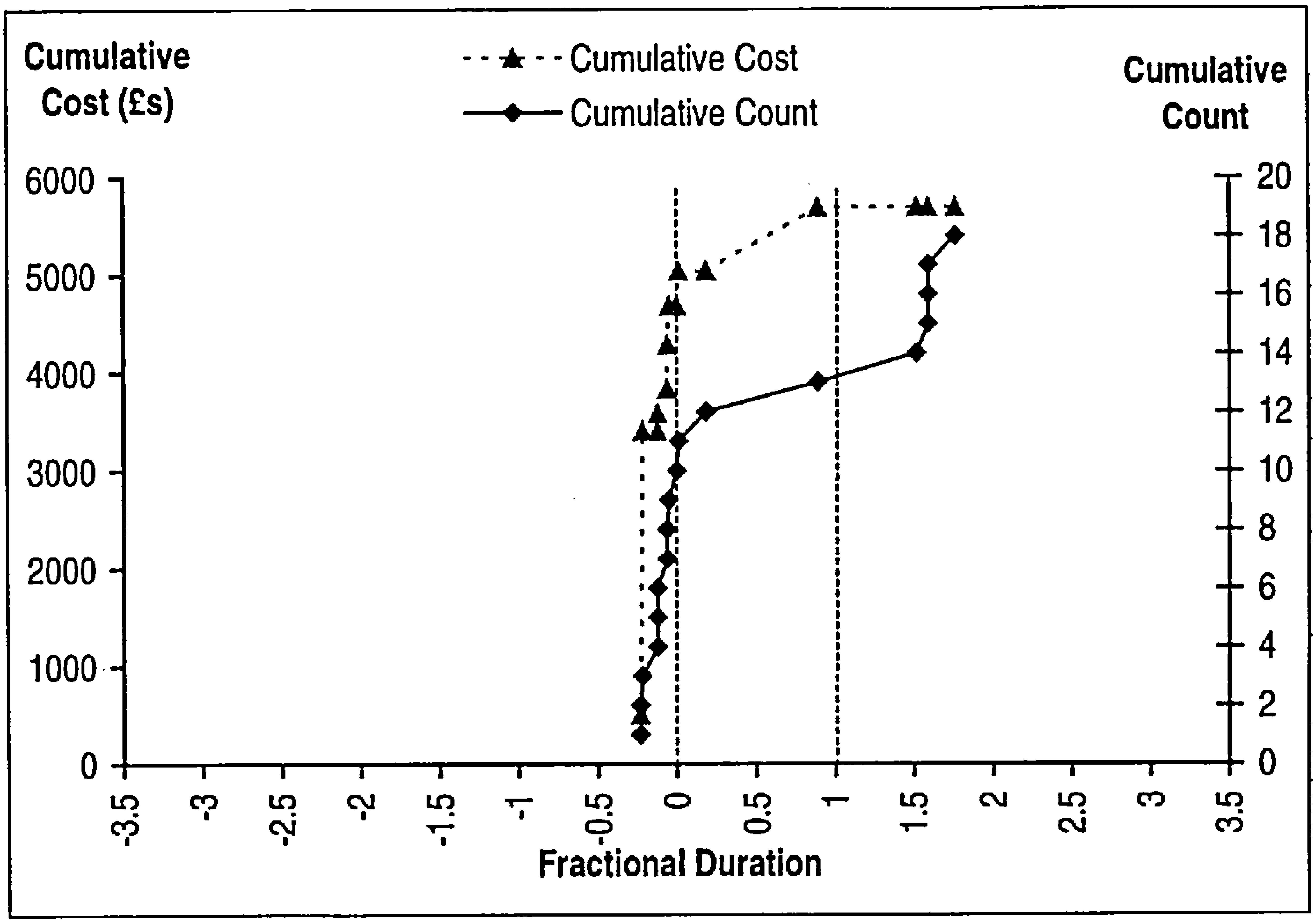


Figure C.11 – WP 4010: Structural Steel Work

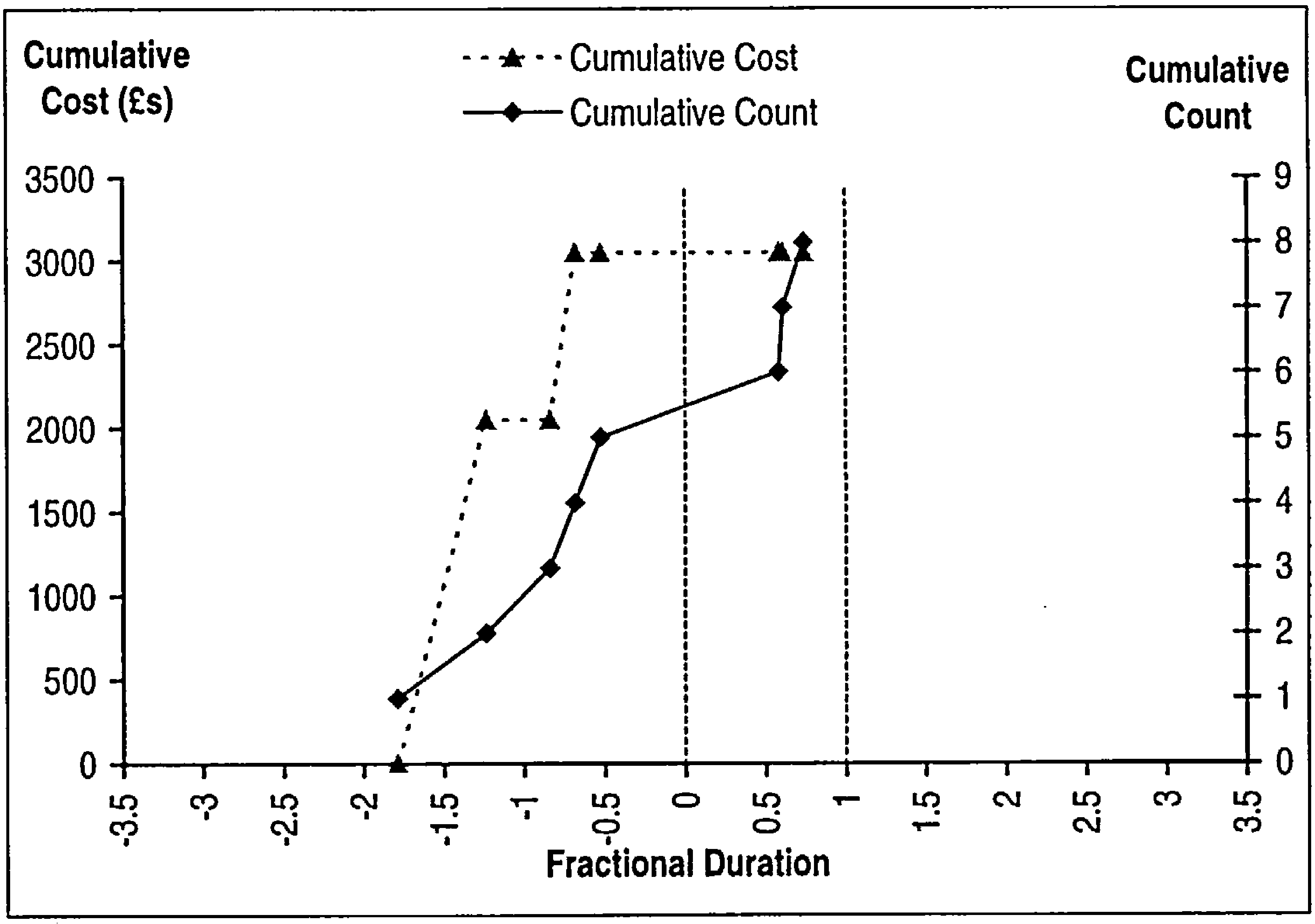


Figure C.12 – WP 4020-2: Office Roof

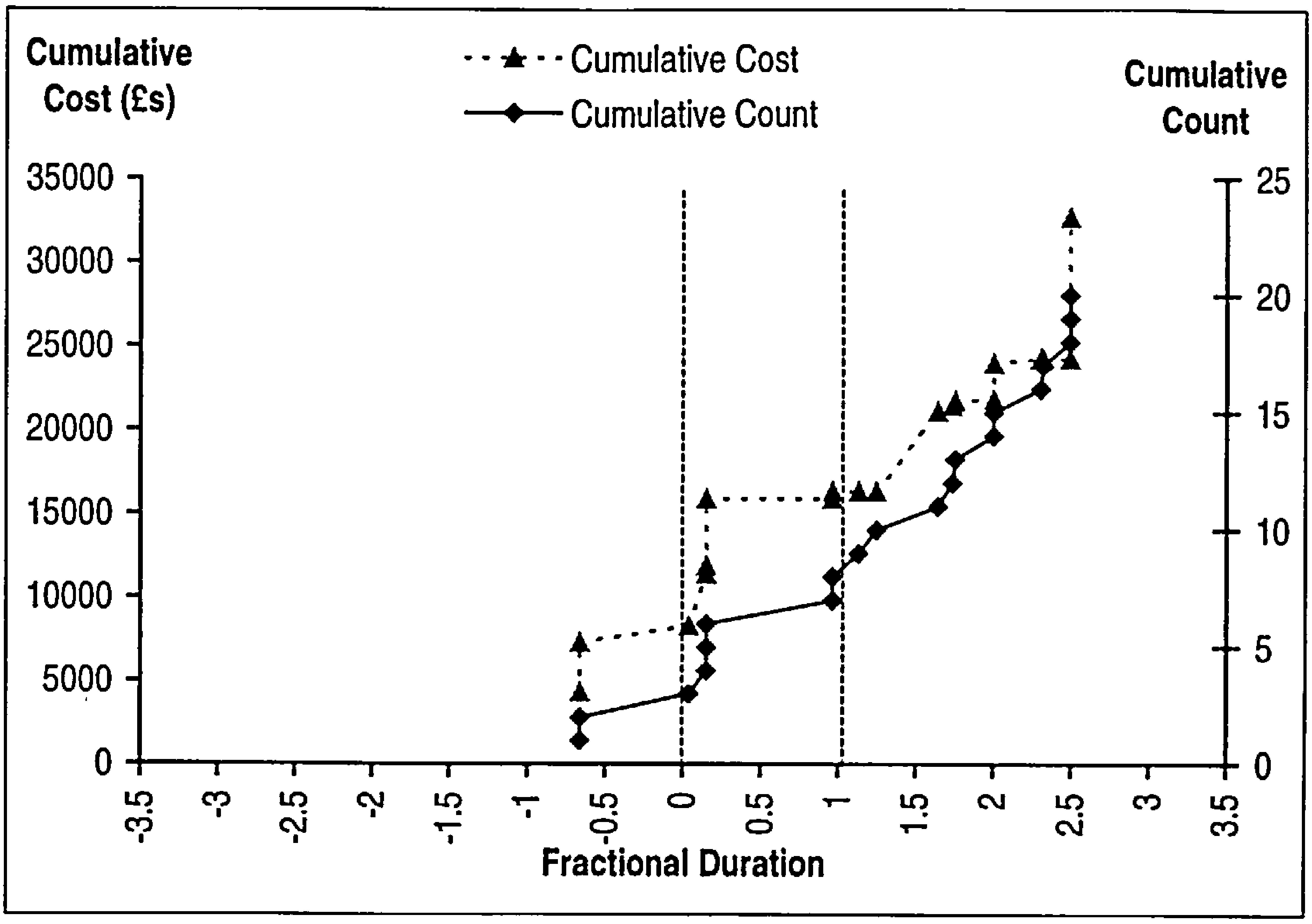


Figure C.13 – WP 4025: Cladding/Covering

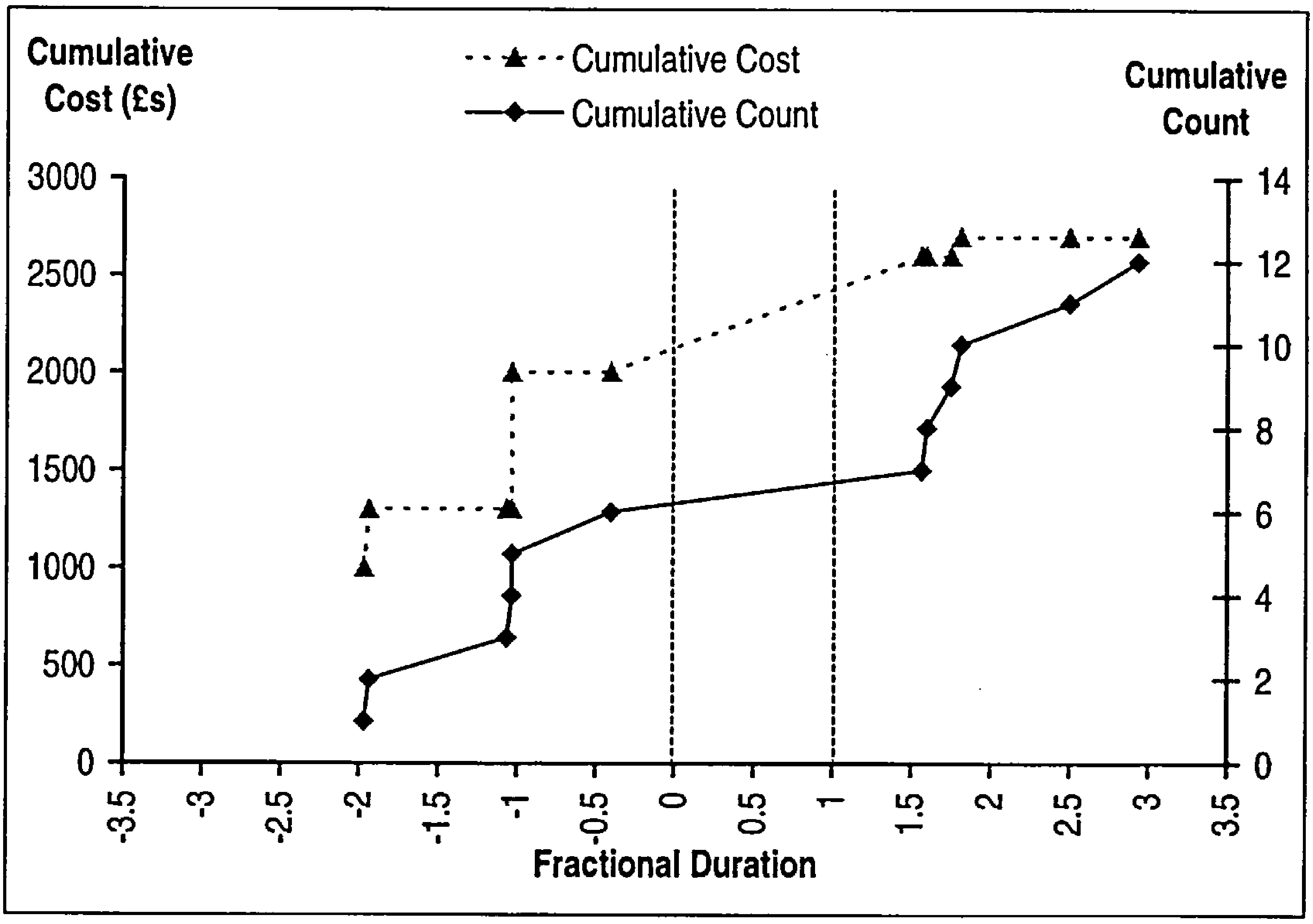


Figure C.14 – WP 4030: Curtain Walling

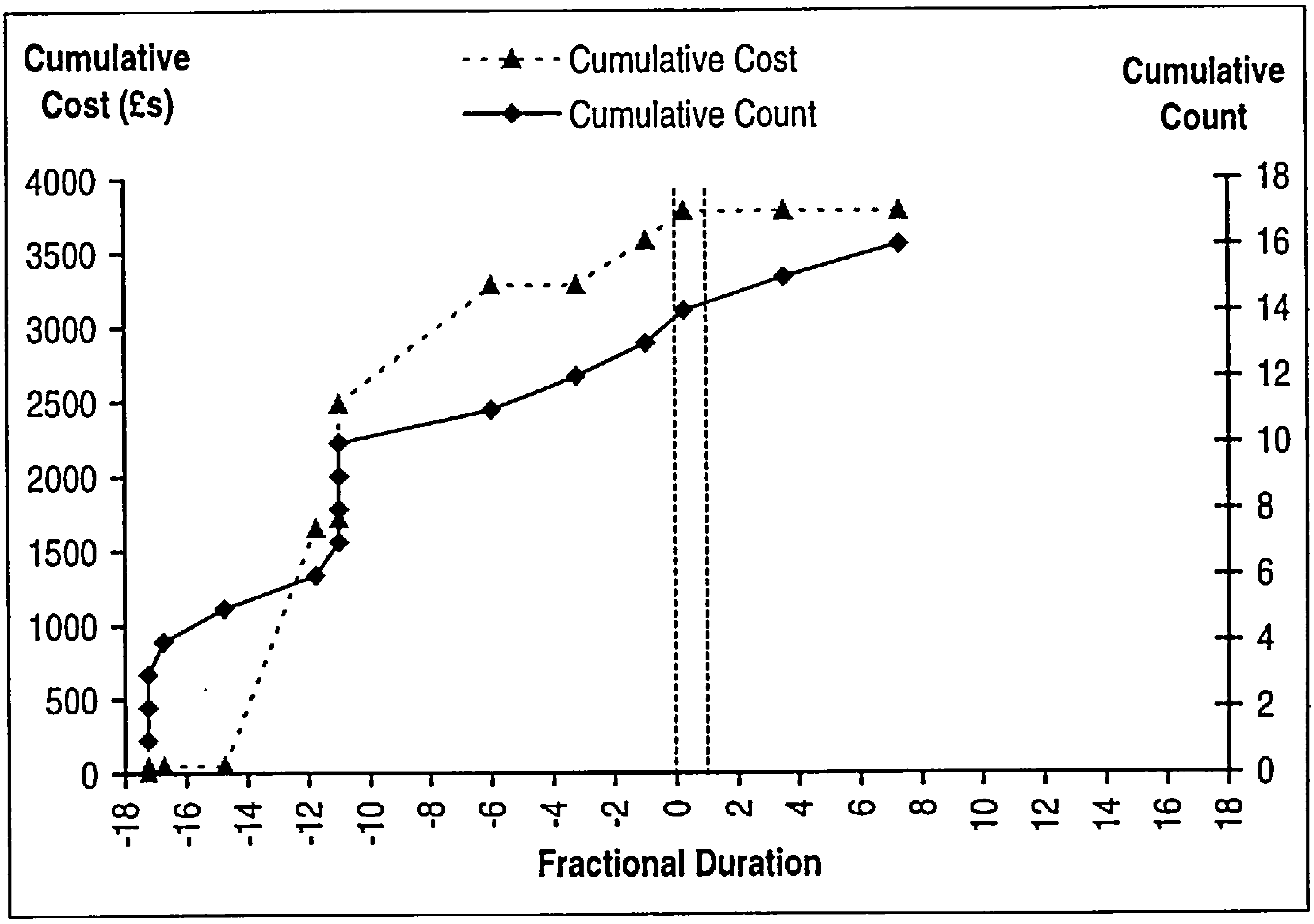


Figure C.15 – WP 4035-1: Doors and Ironmongery

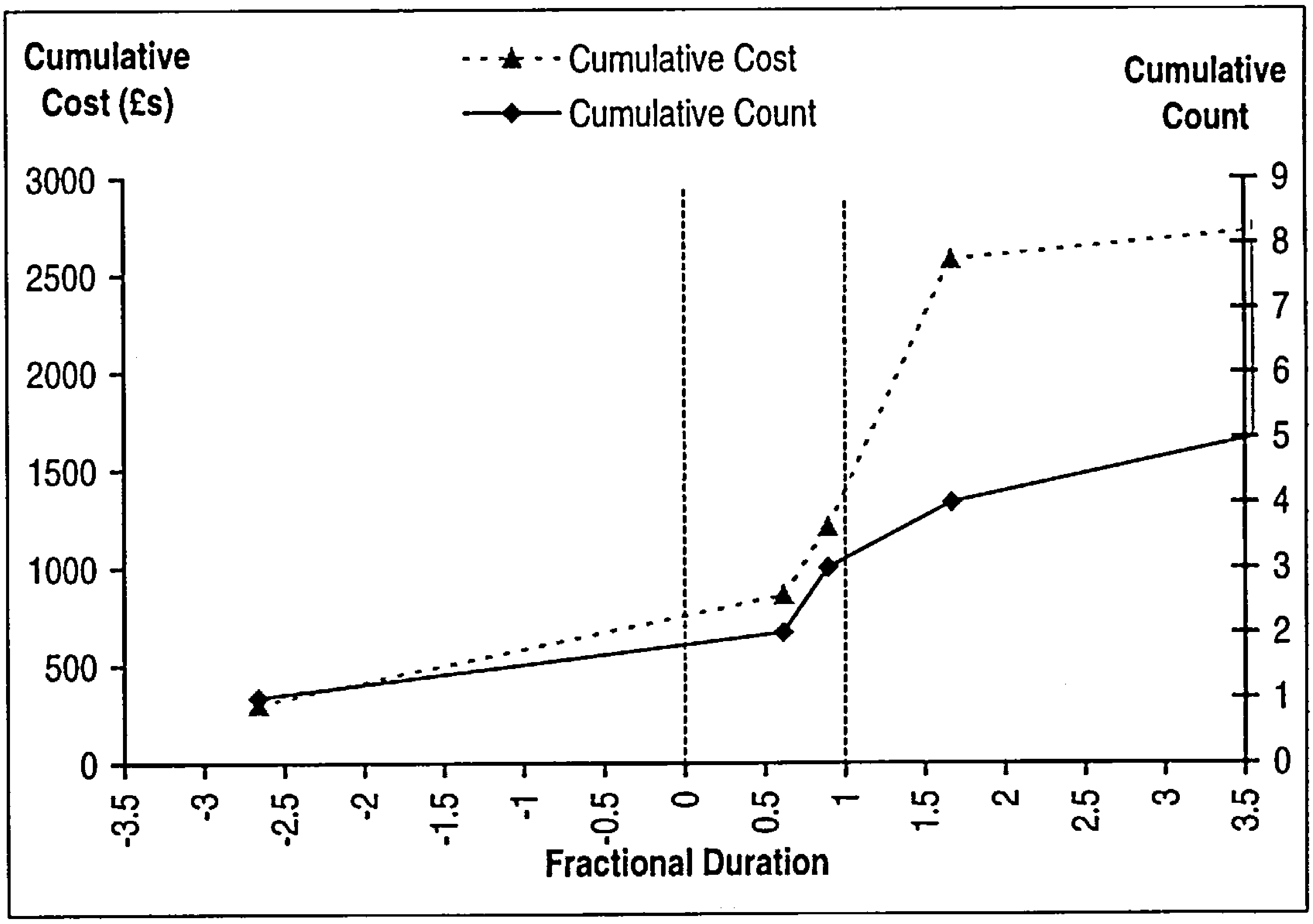


Figure C.16 – WP 4035-2: Metal Doors/Hatches

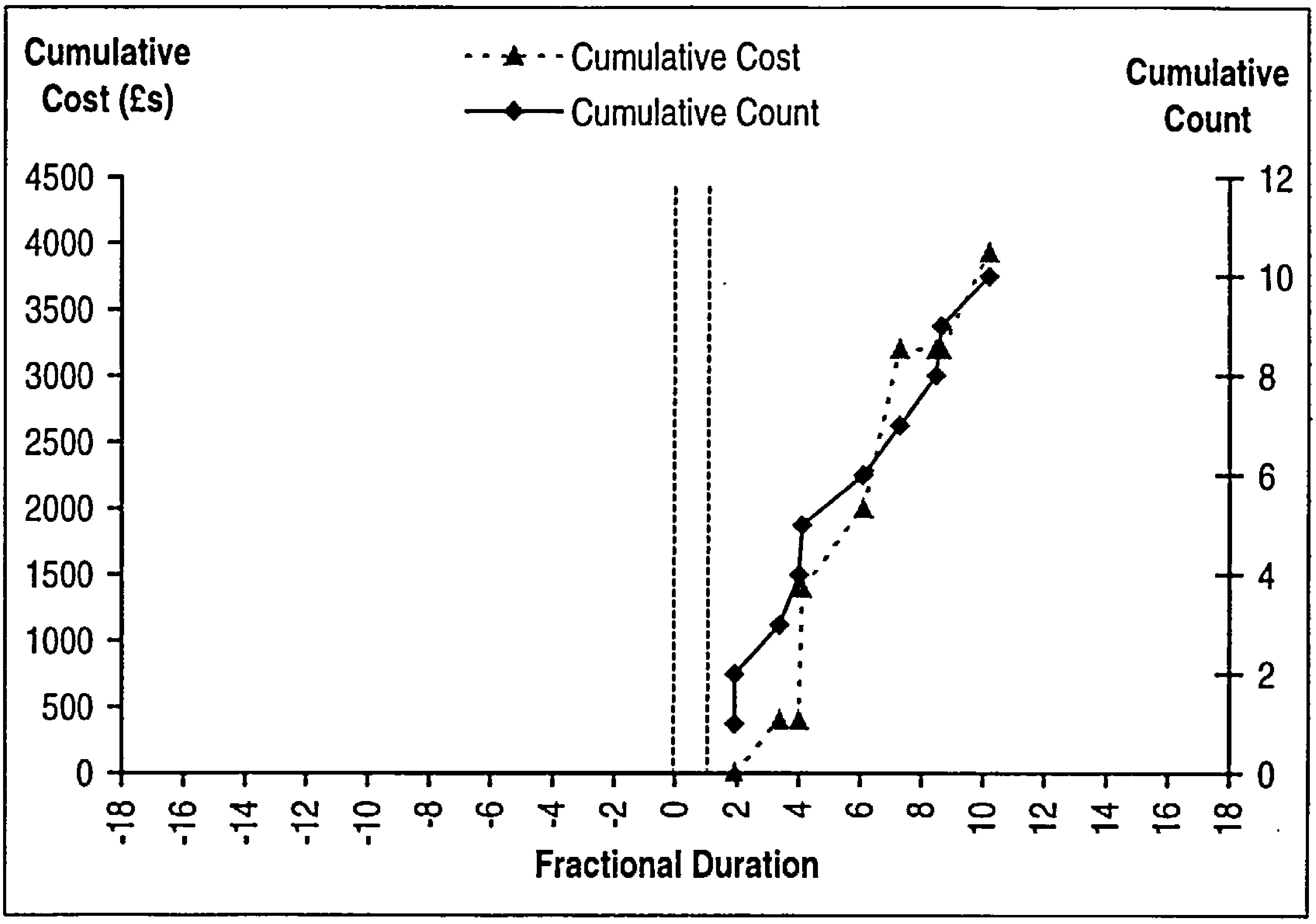


Figure C.17 – WP 4035-3: Balustrading

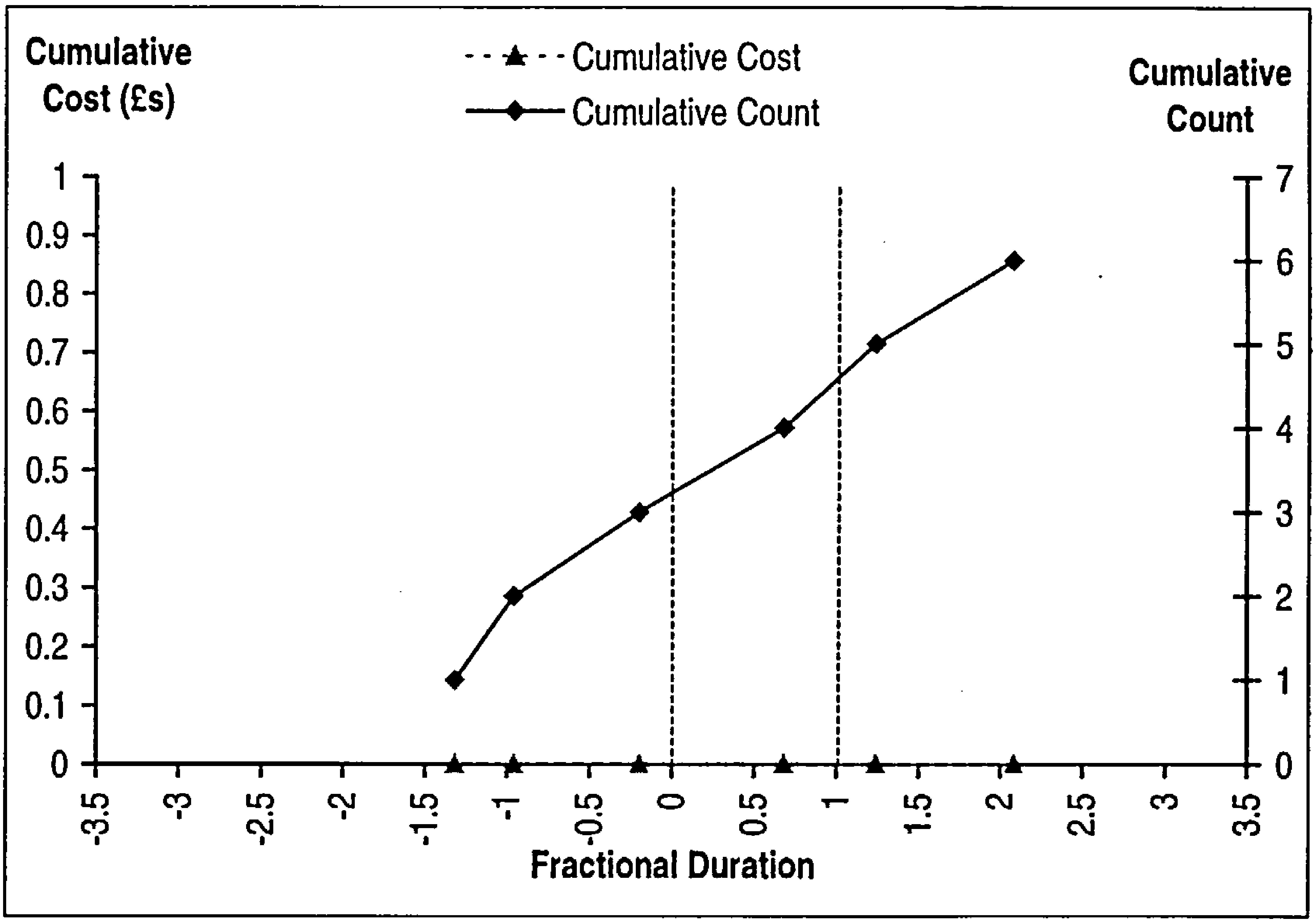


Figure C.18 – WP 4040-1: Windows and Louvres

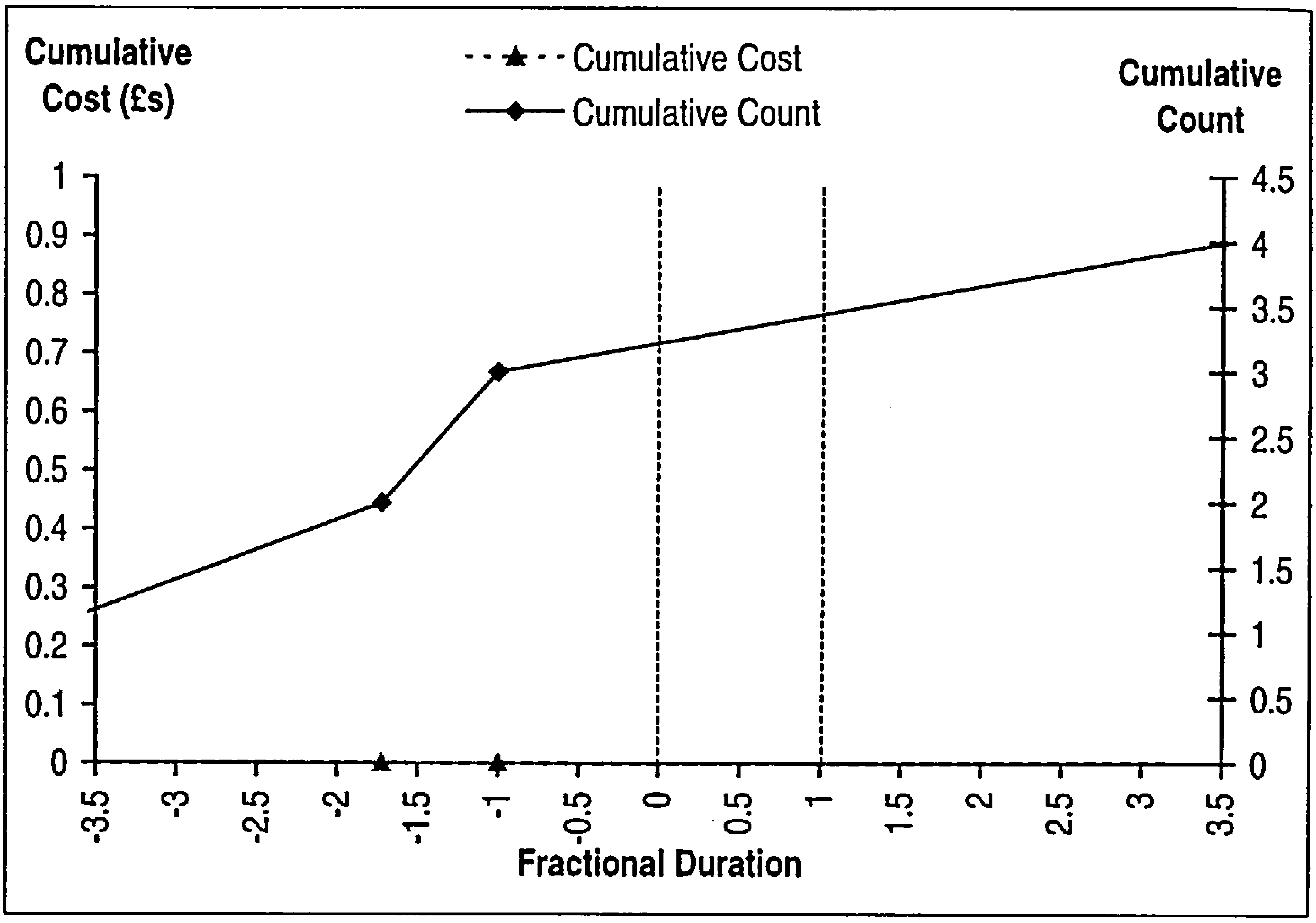


Figure C.19 – WP 4040-2: Solar Screens

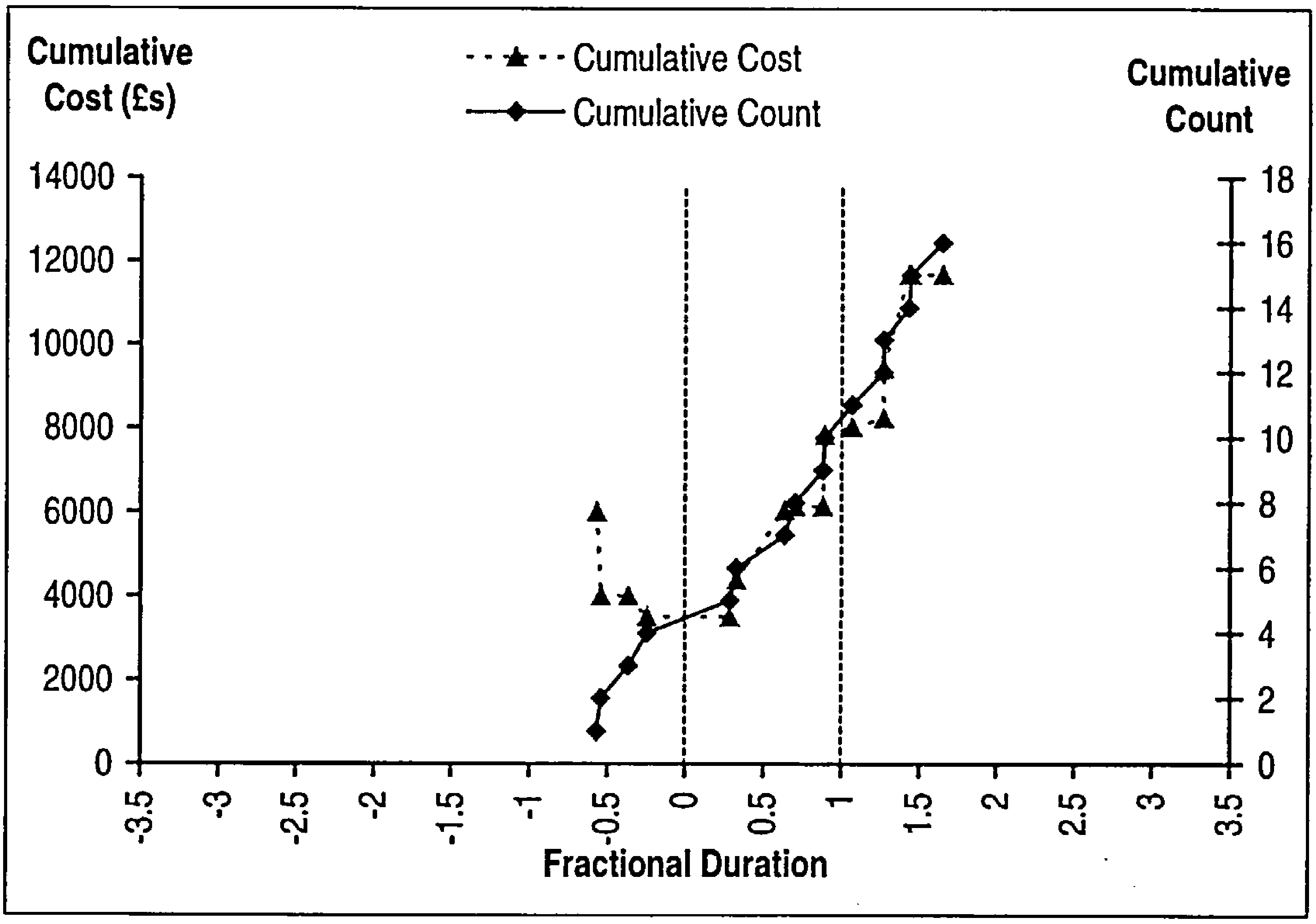


Figure C.20 – WP 5010: Brickwork/Blockwork and Plaster

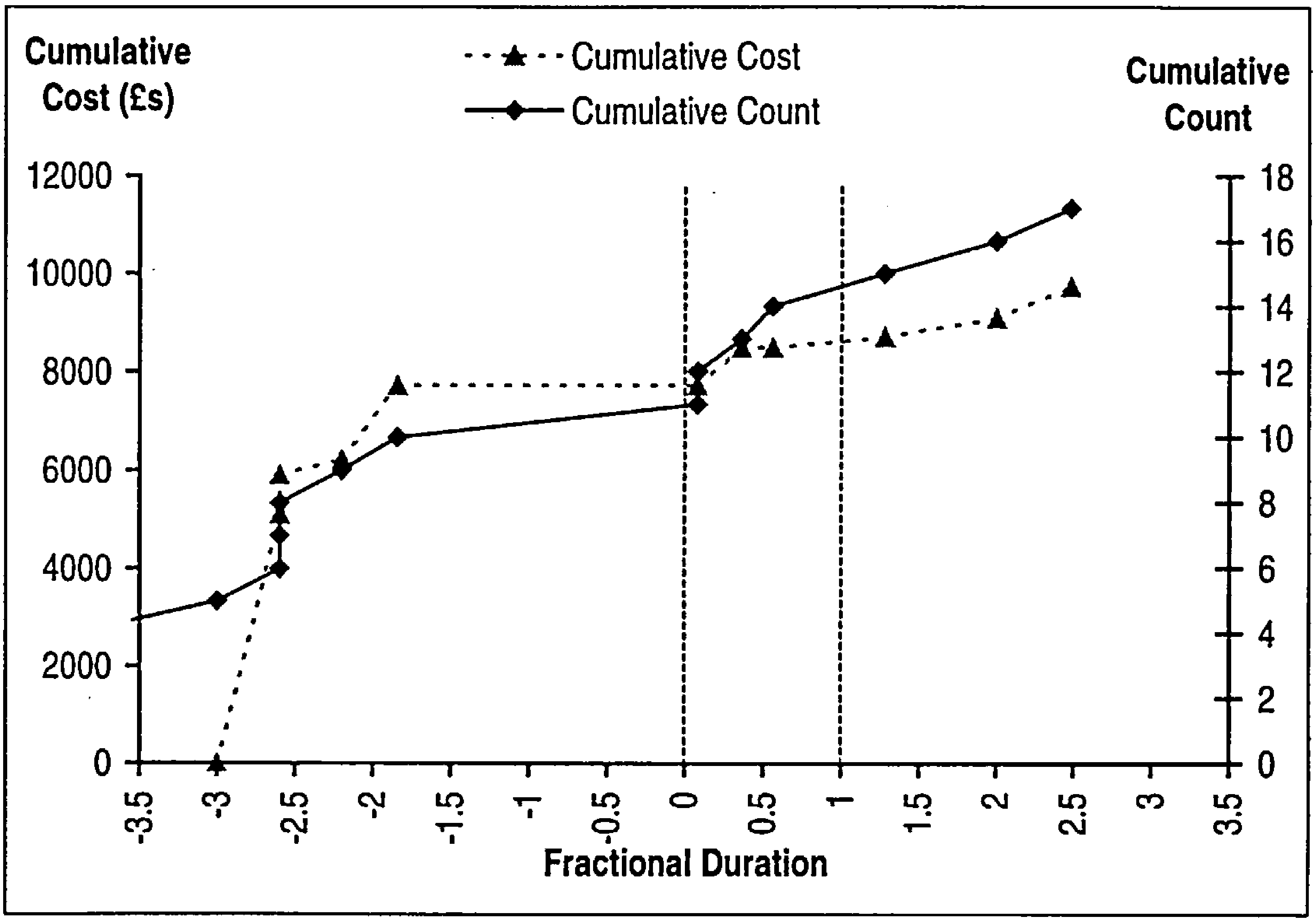


Figure C.21 – WP 5020: Ceiling Finishes

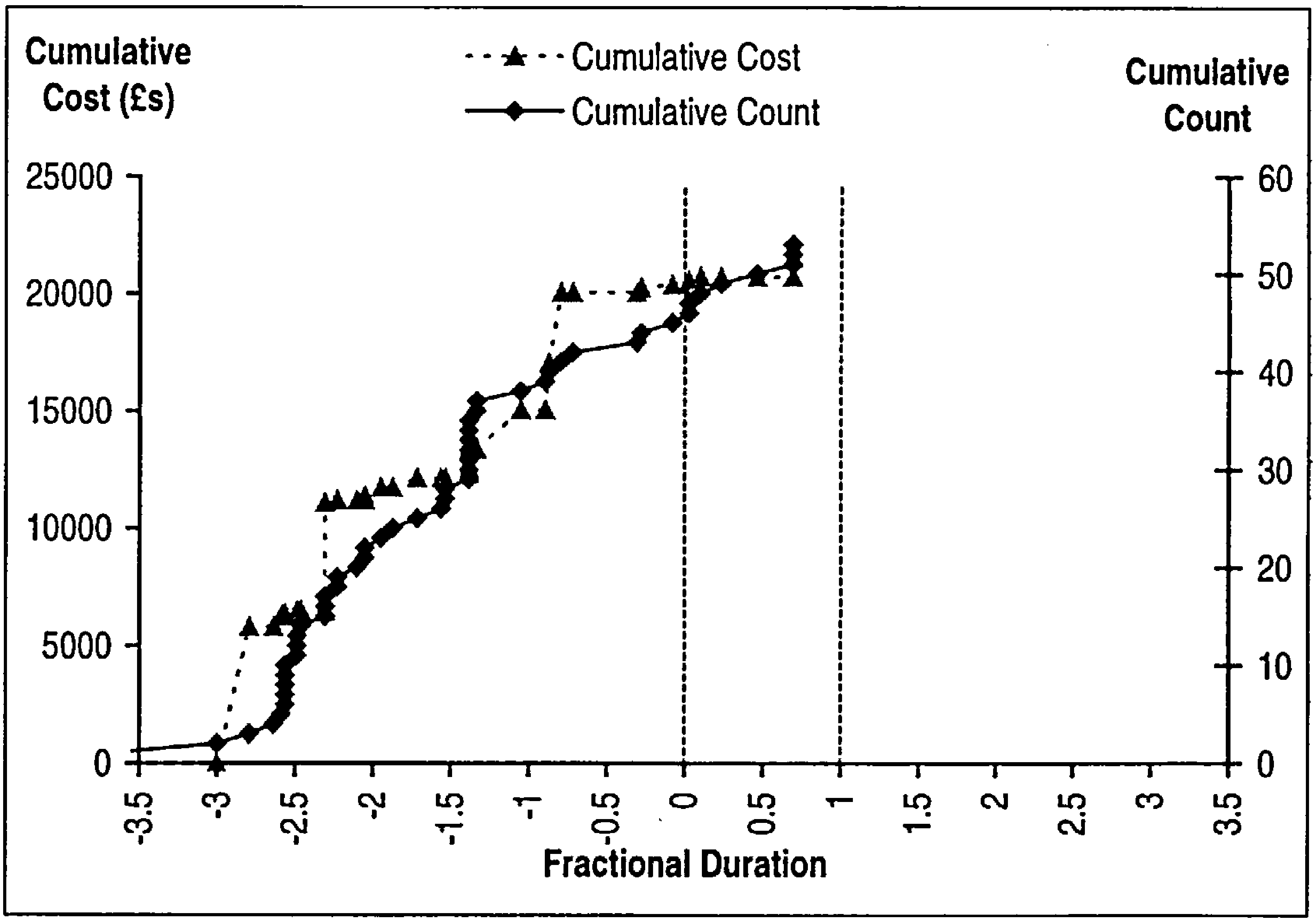


Figure C.22 – WP 5060 Fittings and Furnishings

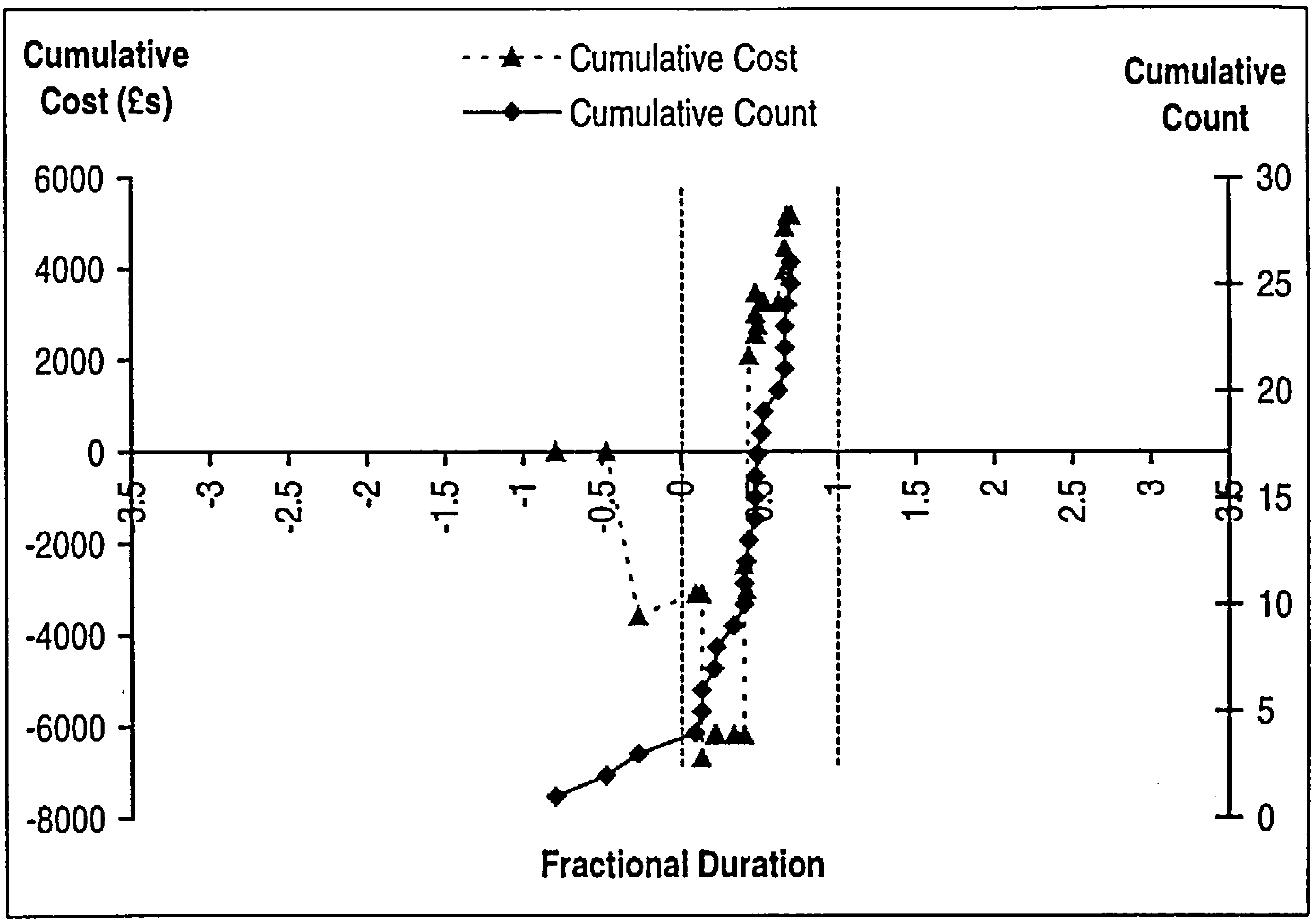


Figure C.23 – WP 6010-1: Building Services – Electrical

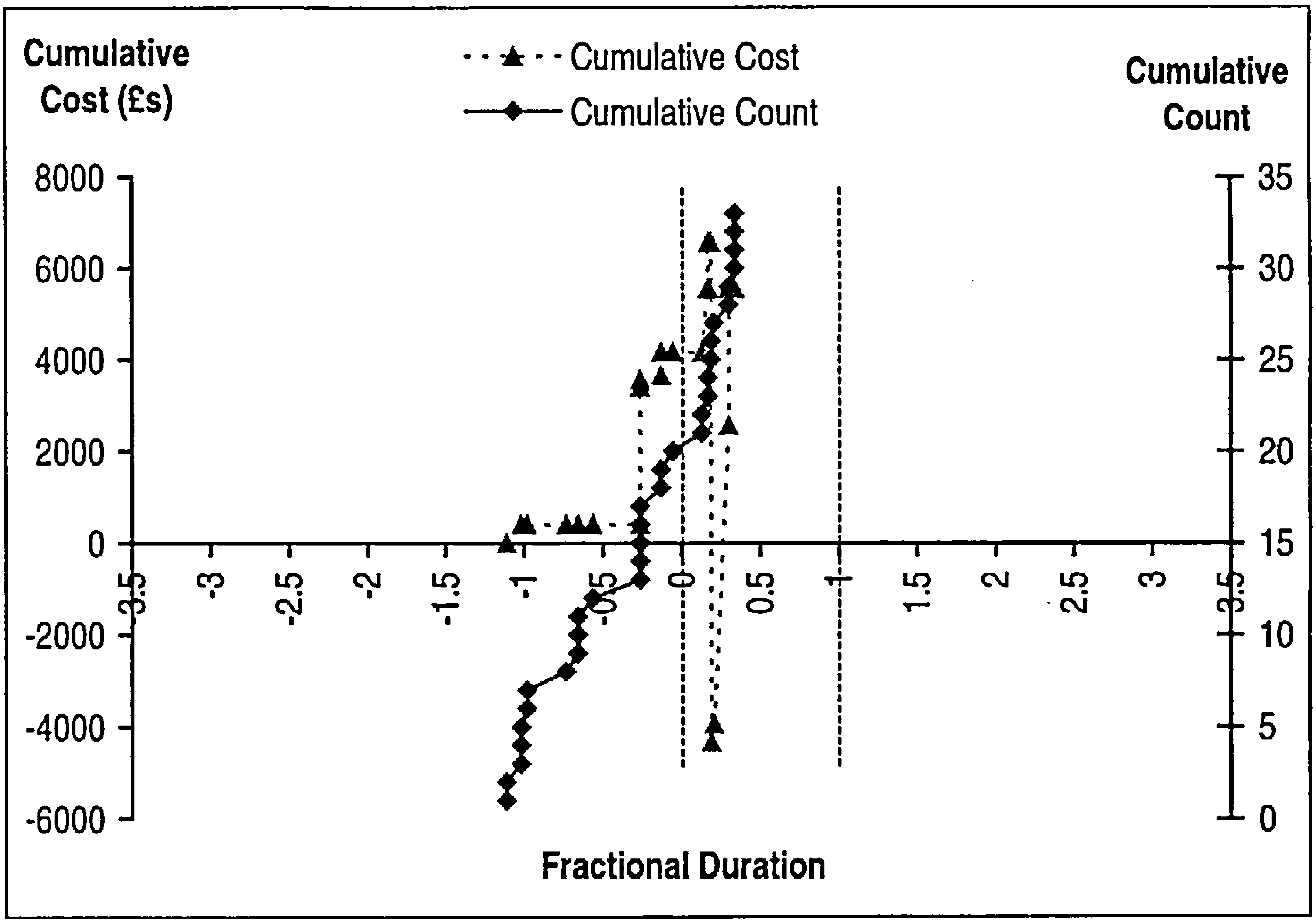


Figure C.24 – WP 7010-1: Building Services - Mechanical

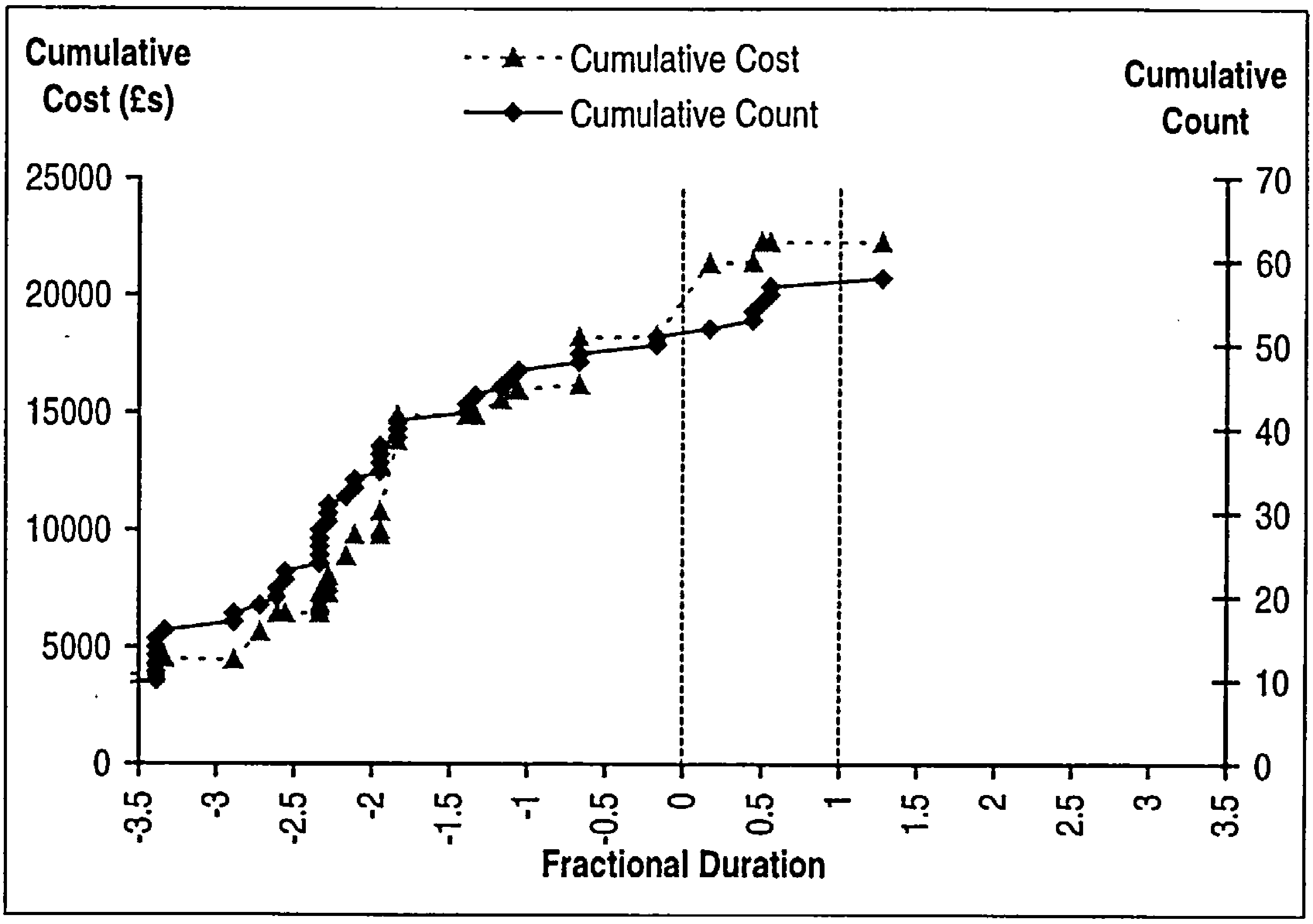


Figure C.25 – WP 7010-2: Building Services - Mechanical

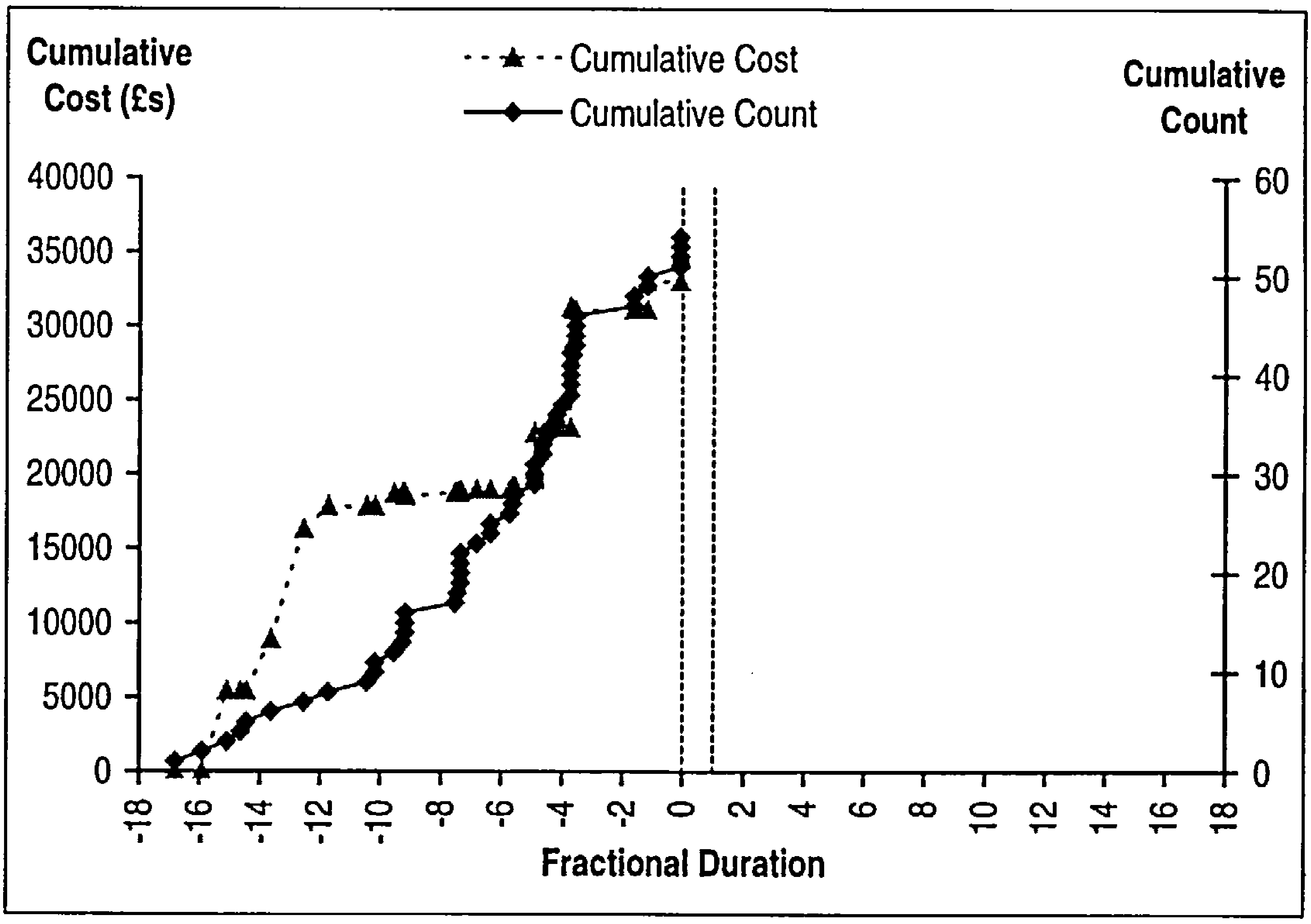


Figure C.26 – WP 9010: External Works

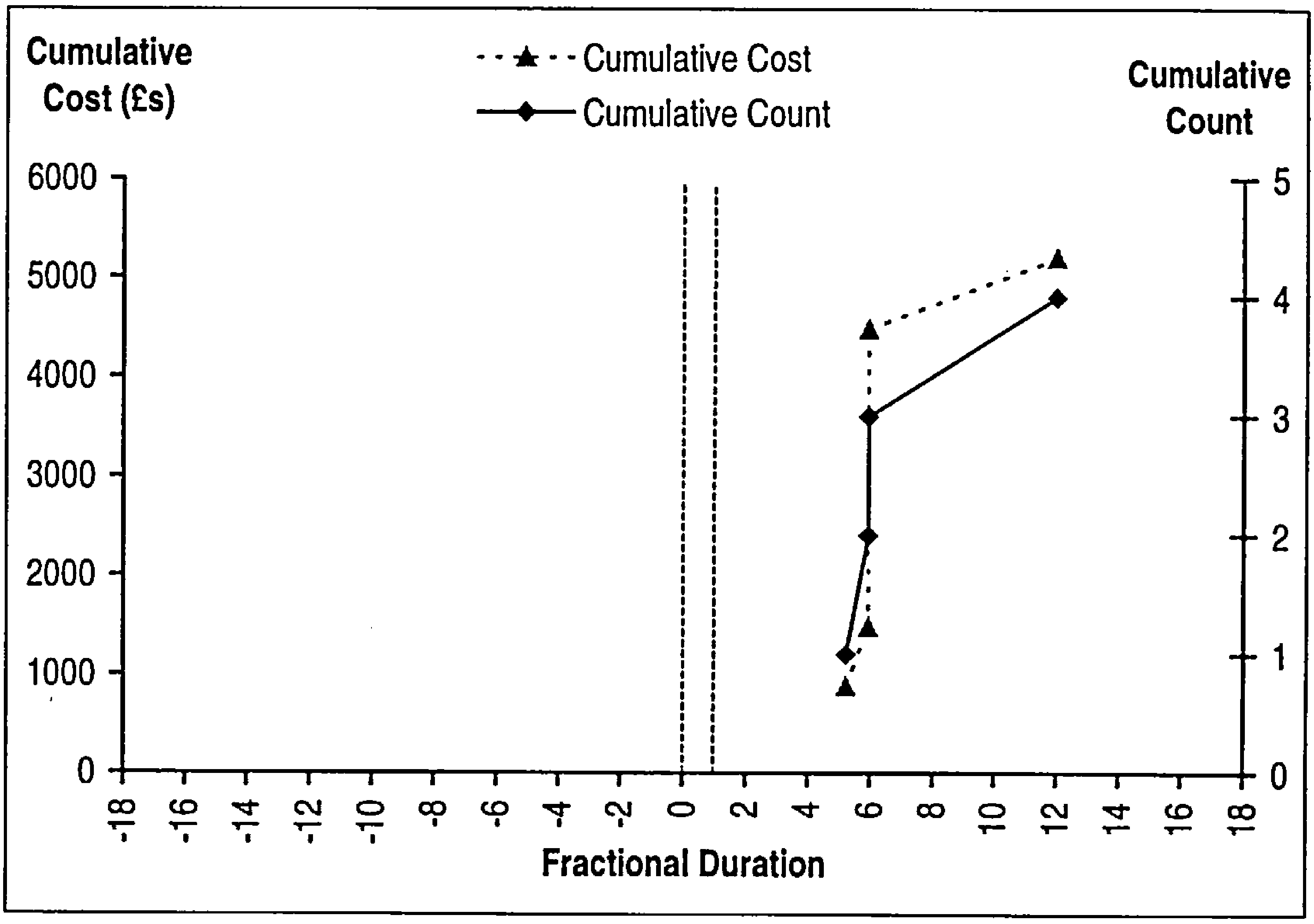


Figure C.27 – WP 9020: Site Works

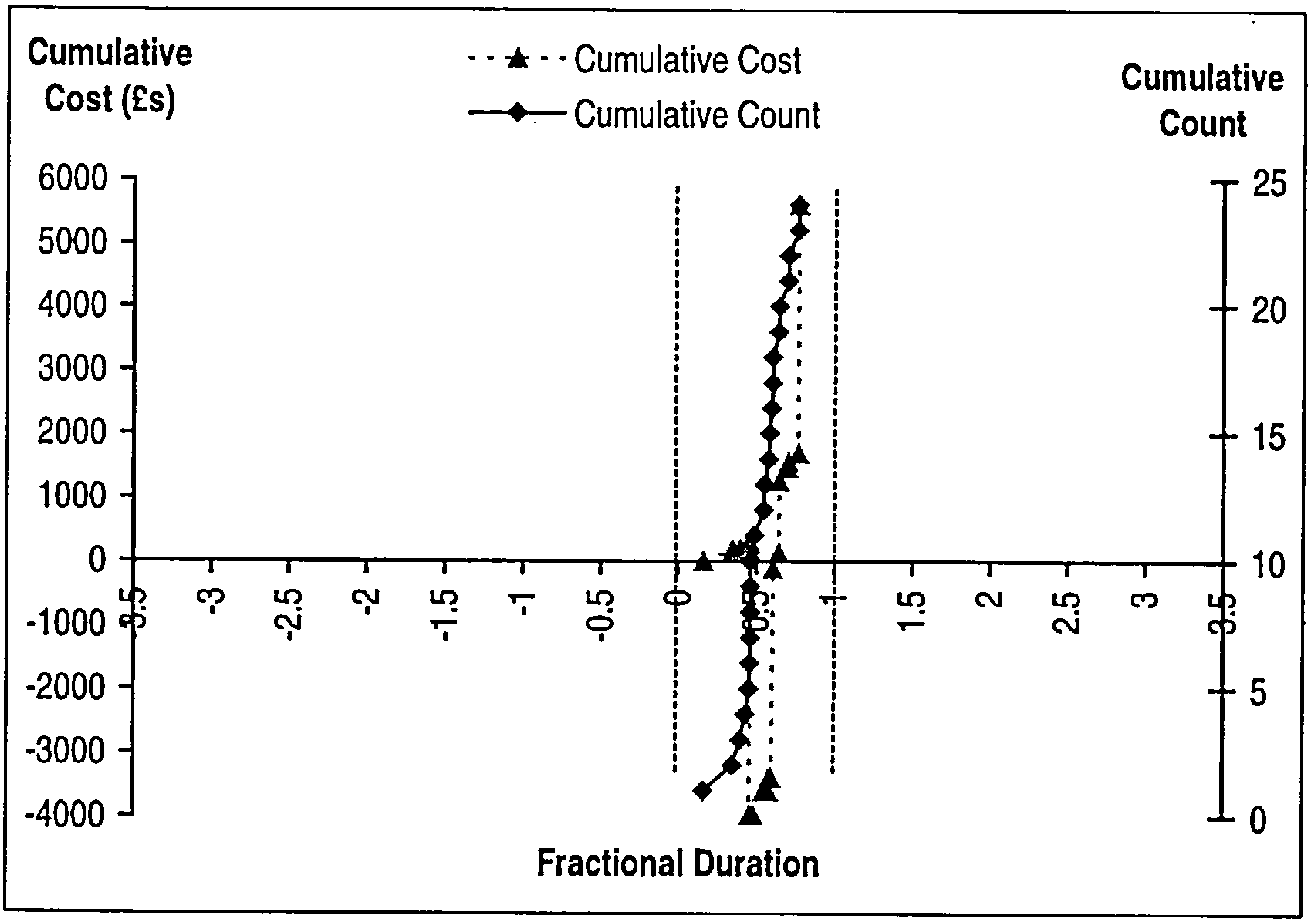


Figure C.28 – WP 10040: Tenant Fit-out

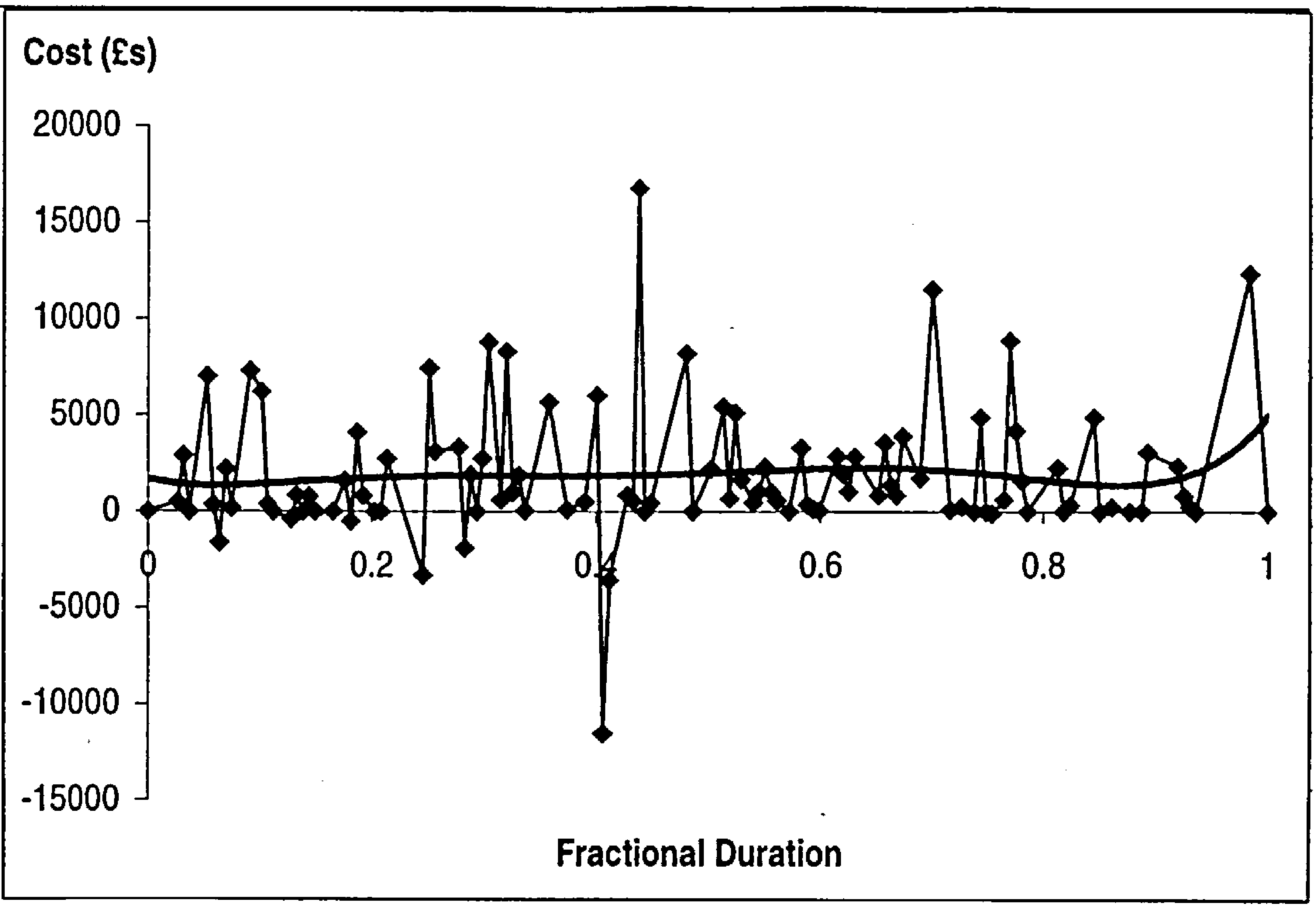


Figure C.29 – Change Order Request Costs: All Change Orders Over the Entire Period When Change Orders Were Used

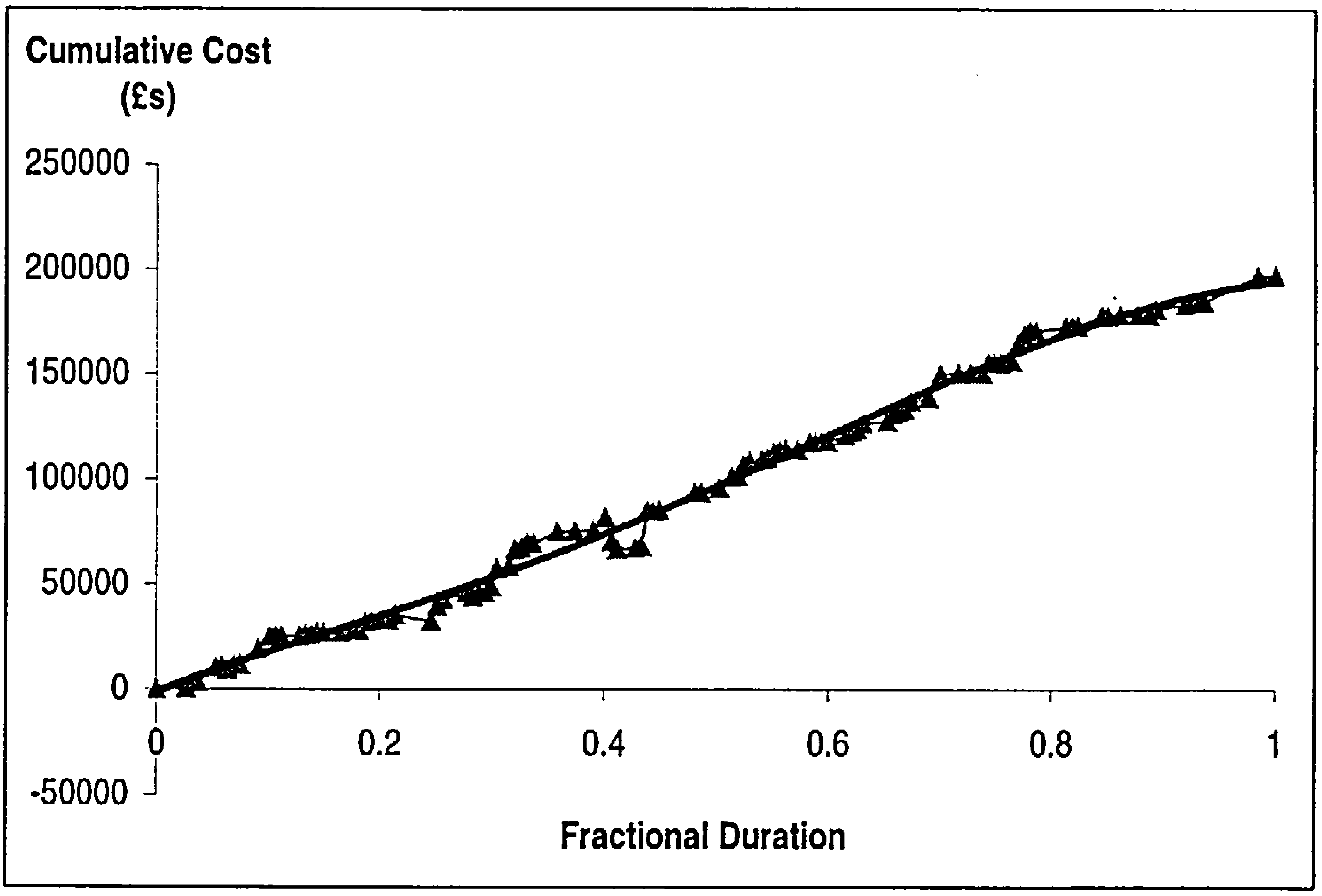


Figure C.30 – Cumulative Cost of All Change Orders Over the Entire Period When Change Orders Were Used

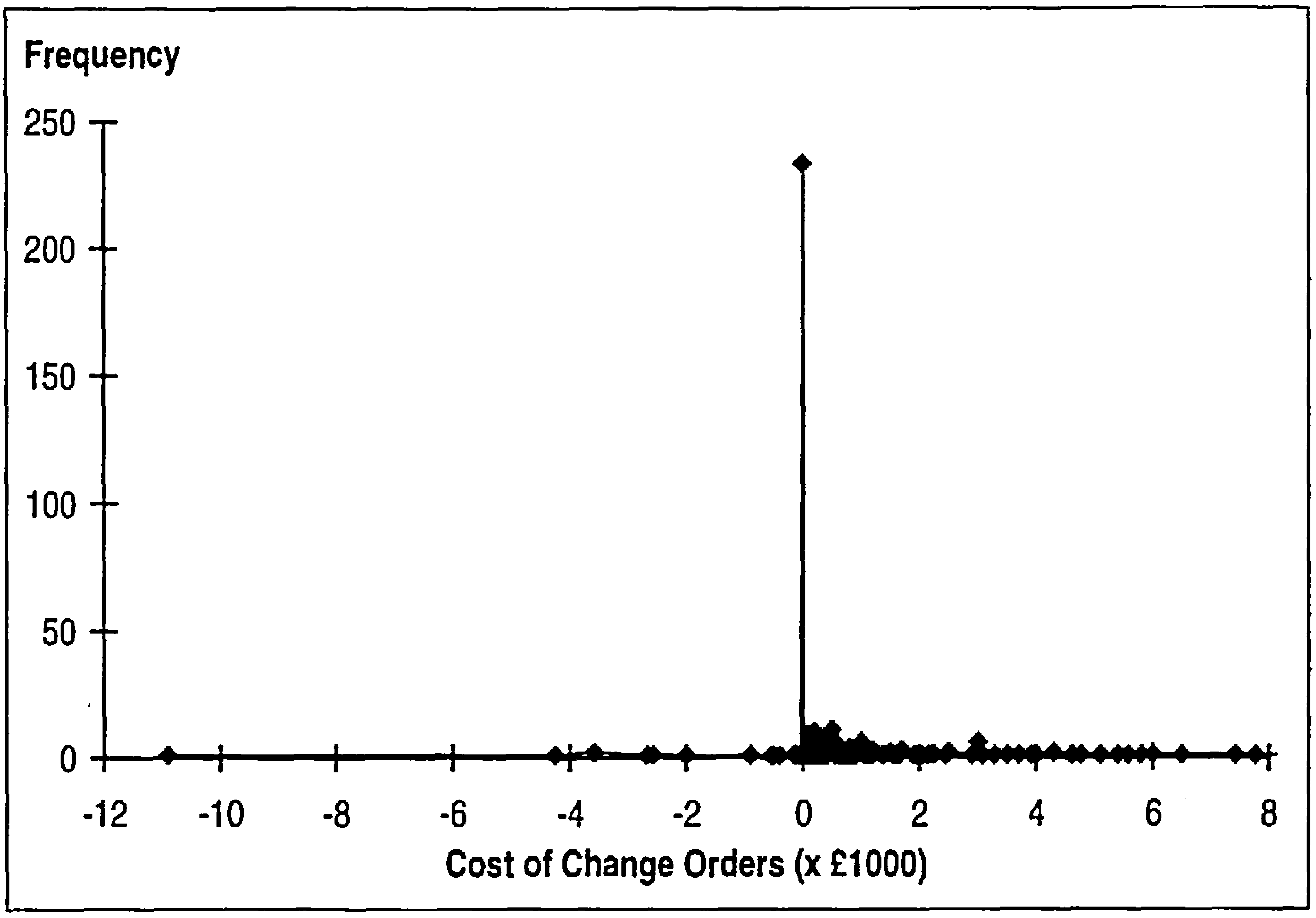


Figure C.31 – Change Order Cost Distribution: Raw Data

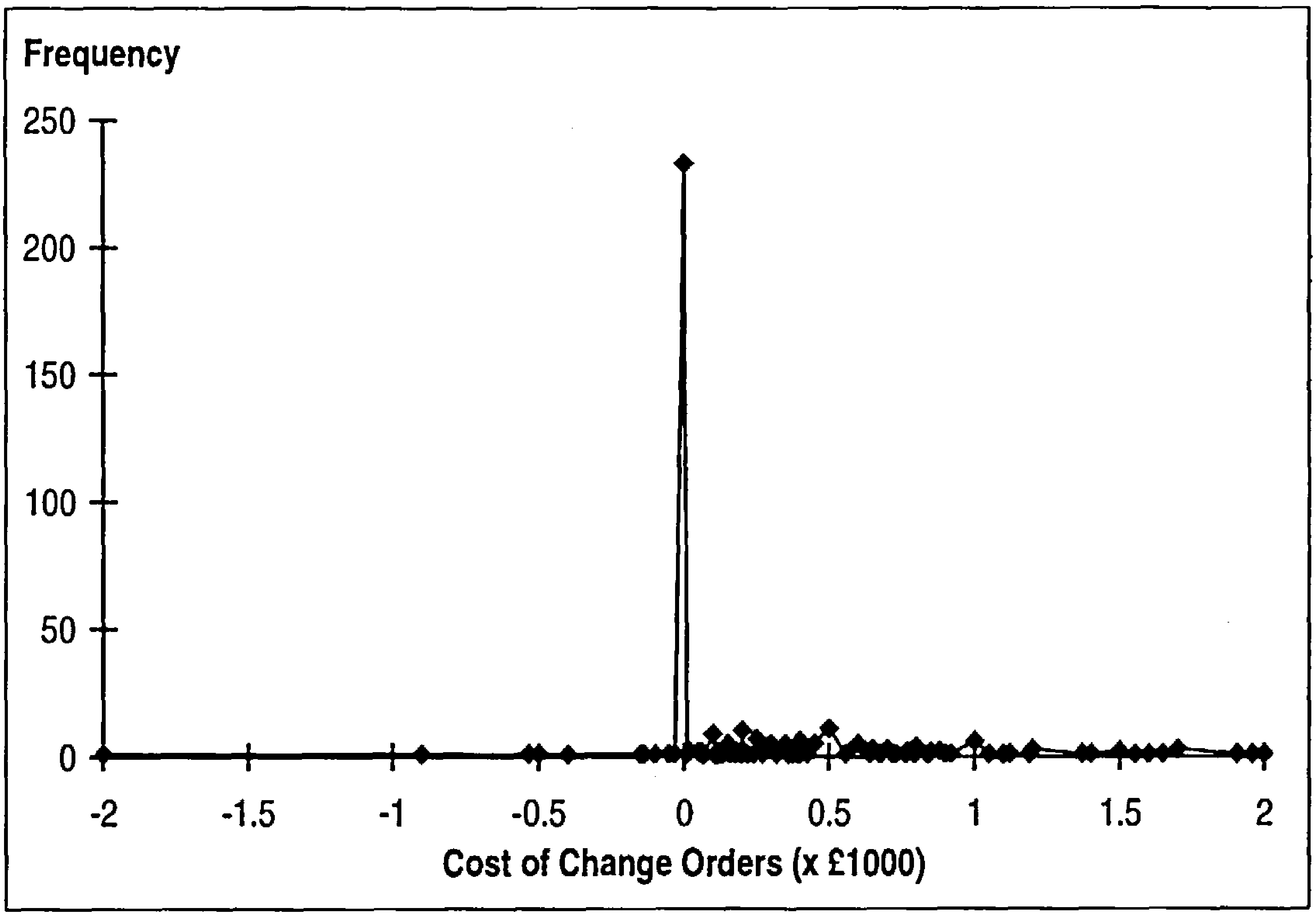


Figure C.31b – Change Order Cost Distribution: Raw Data (-£2000 to £2000)

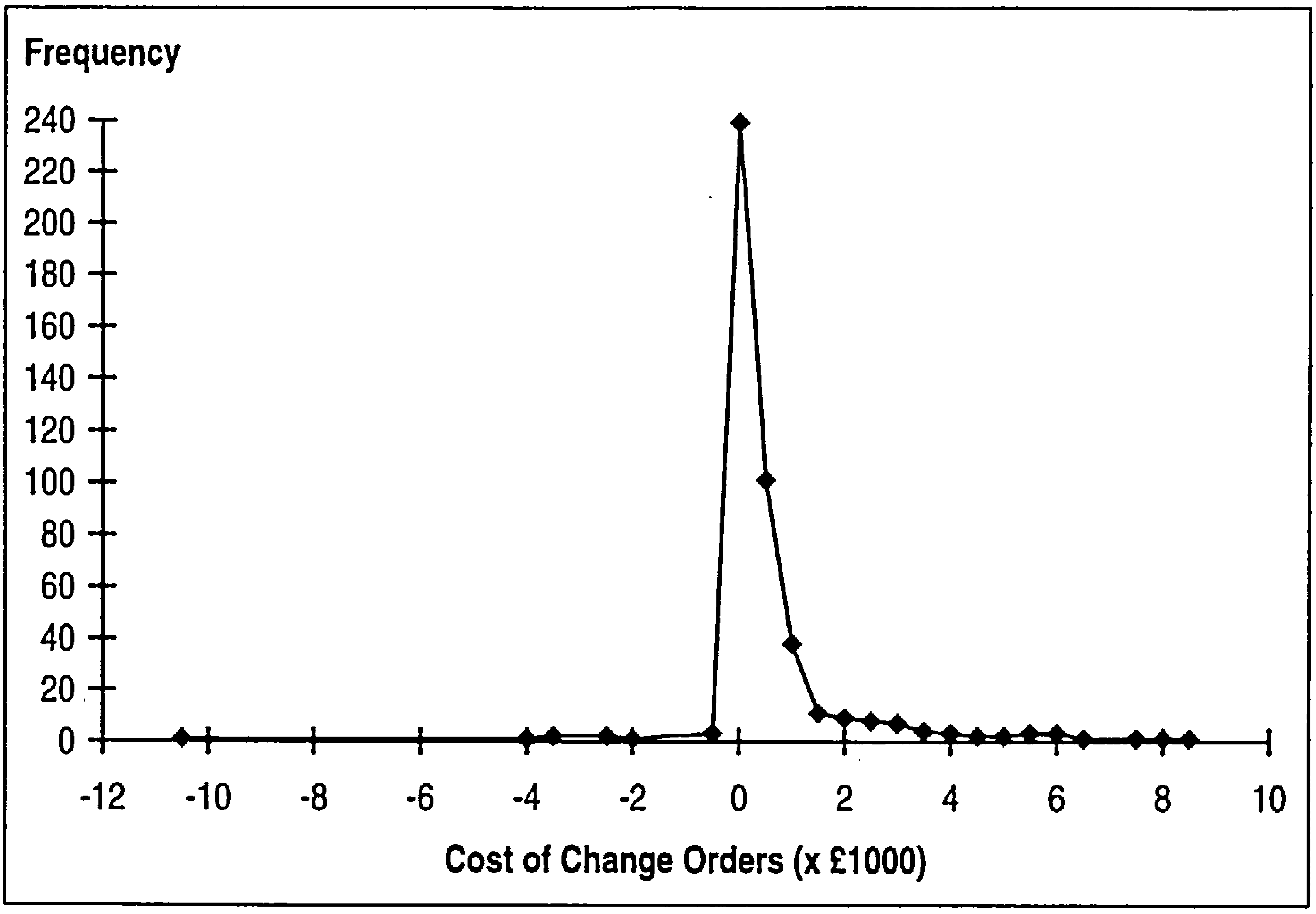


Figure C.32 – Distribution of Change Order Costs: Cost Class Intervals of £500

[BLANK PAGE]

APPENDIX D

List of Figures

Figure D.1 – Change Order Costs Associated With Each Reason Category................................ 2
Figure D.2 – Change Order Costs: Work Package & Reason.. 2
Figure D.3 – Fractional Cost of Change Orders for Each Work Package...................................... 3
Figure D.4 – Number of Change Orders Affecting Each Work Package.. 3
Figure D.5 – Number of Change Orders Specifying Each Reason Category............................... 4
Figure D.6 – Change Order Cost Distribution: Raw Data... 4
Figure D.6b – Change Order Cost Distribution: Raw Data (£0 to £4000)...................................... 5
Figure D.7 – Distribution of Change Order Costs: Cost Class Intervals of £500............................ 5

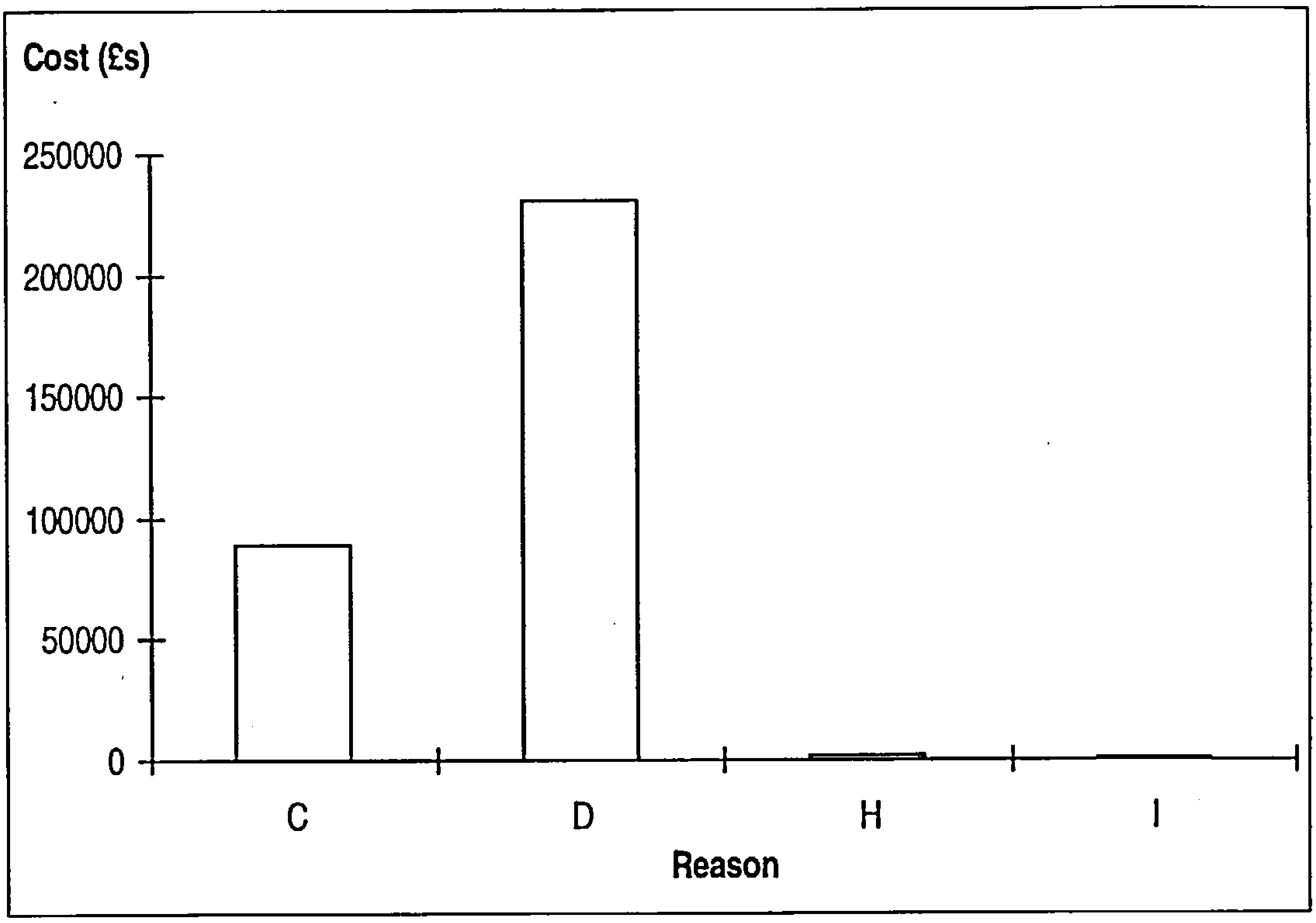


Figure D.1 – Change Order Costs Associated With Each Reason Category

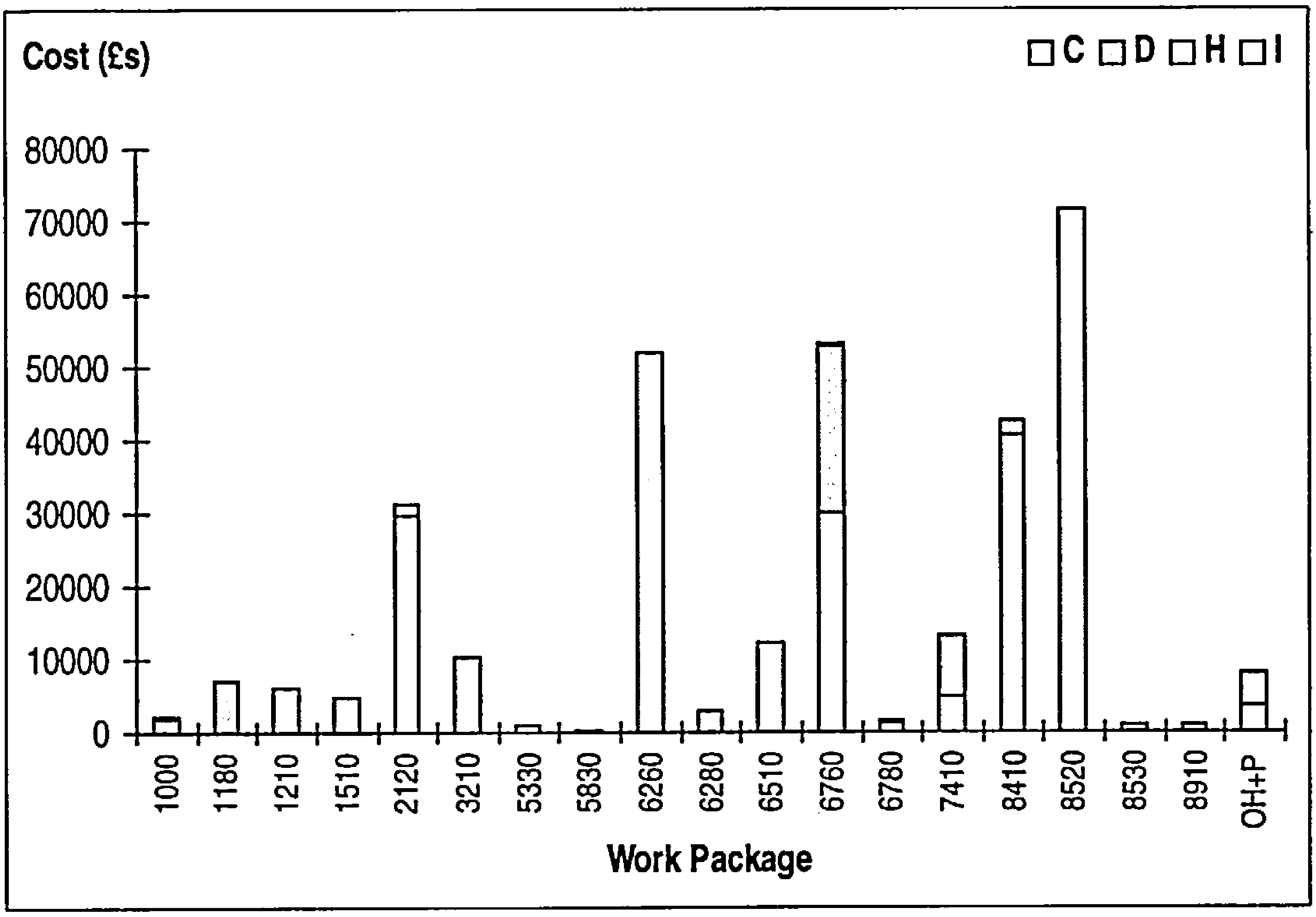


Figure D.2 – Change Order Costs: Work Package & Reason

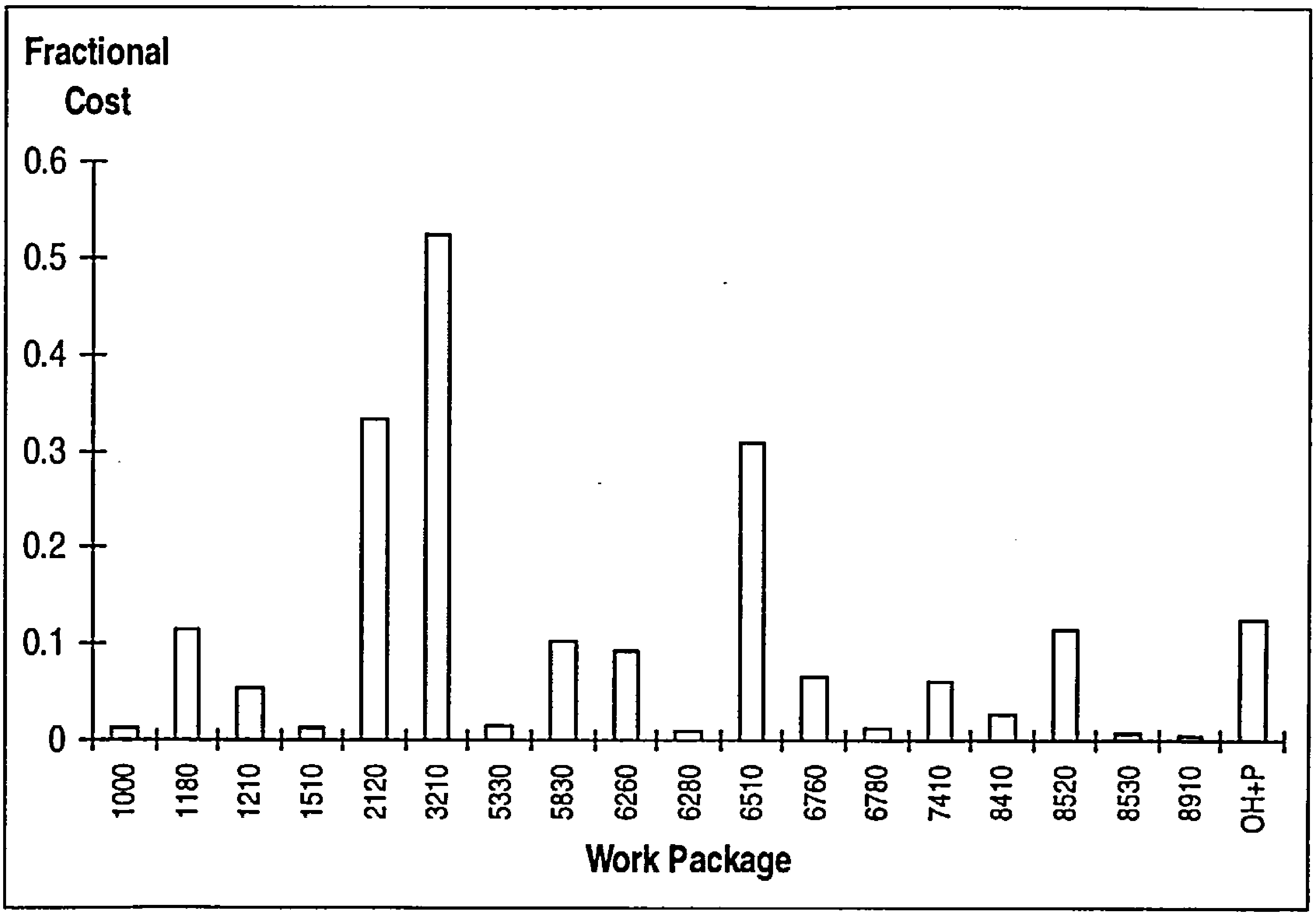


Figure D.3 – Fractional Cost of Change Orders for Each Work Package

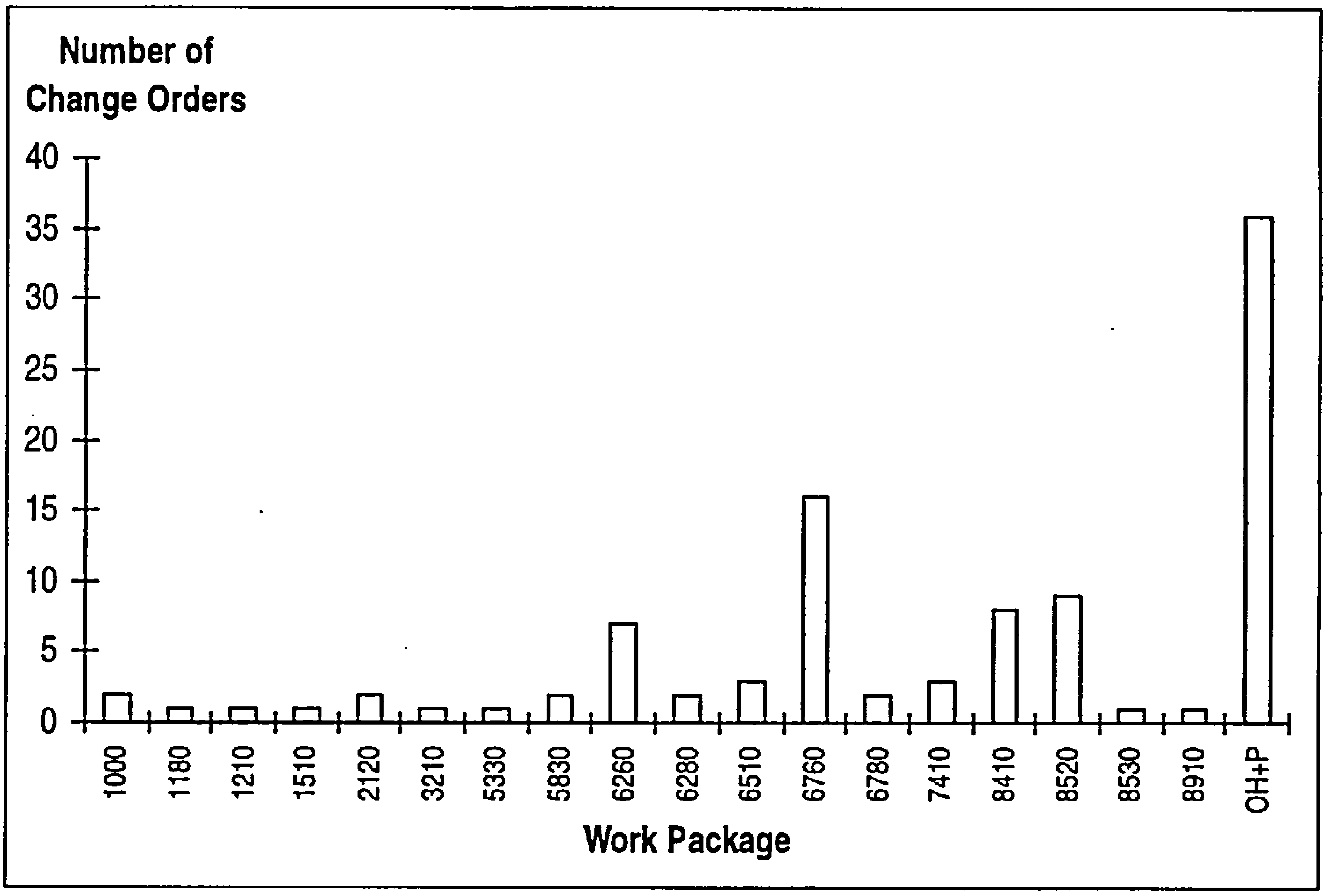


Figure D.4 – Number of Change Orders Affecting Each Work Package

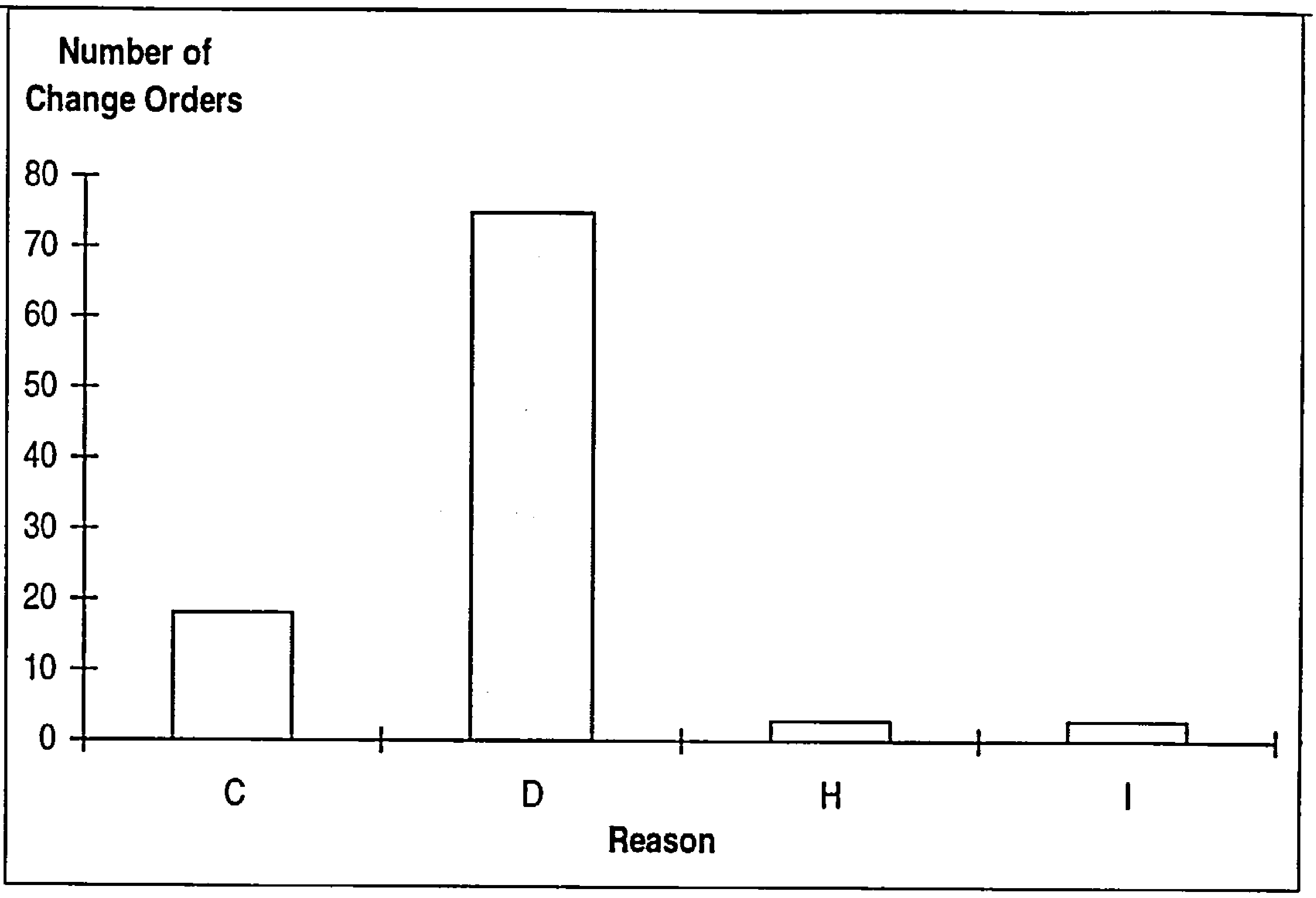


Figure D.5 – Number of Change Orders Specifying Each Reason Category

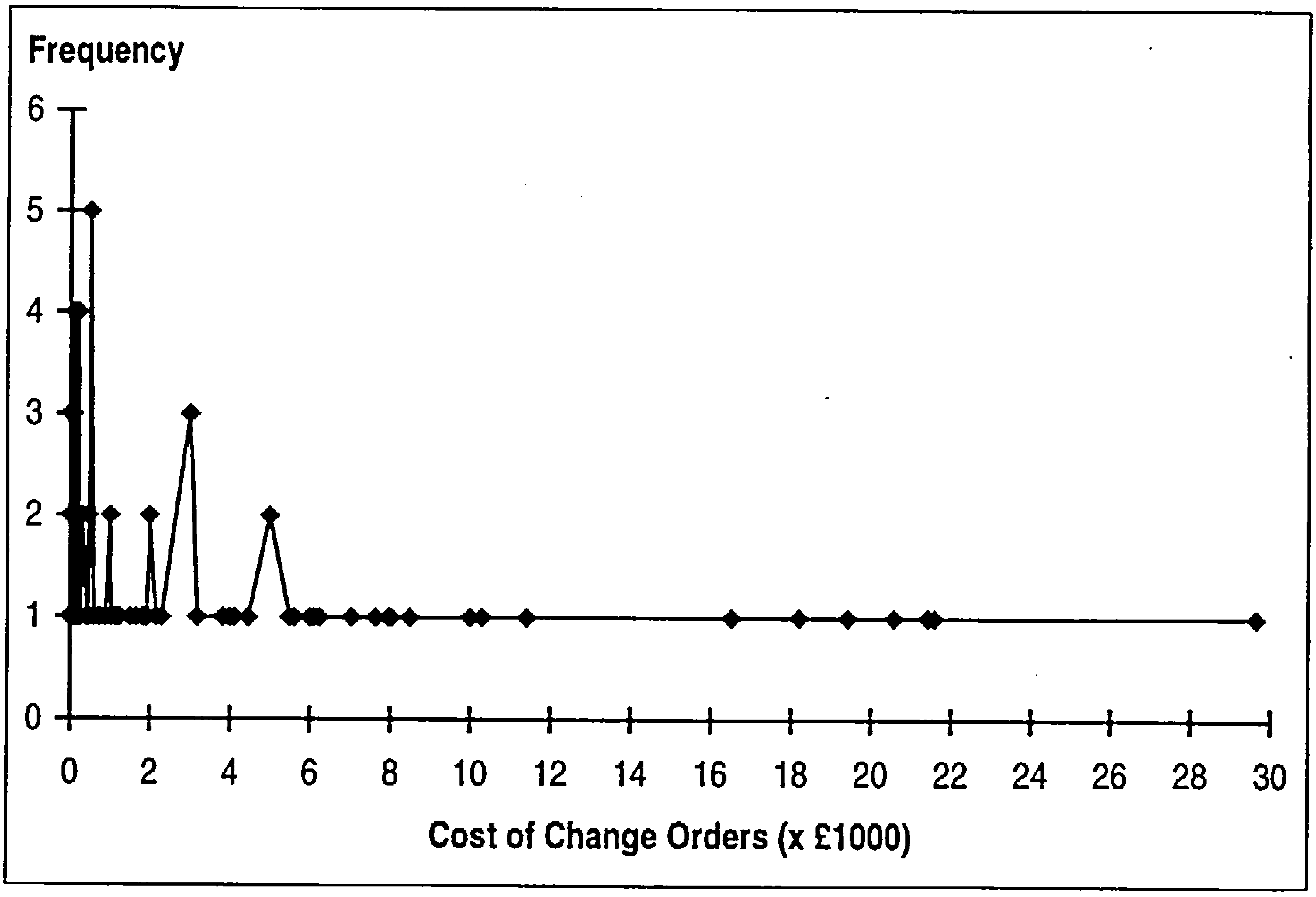


Figure D.6 – Change Order Cost Distribution: Raw Data

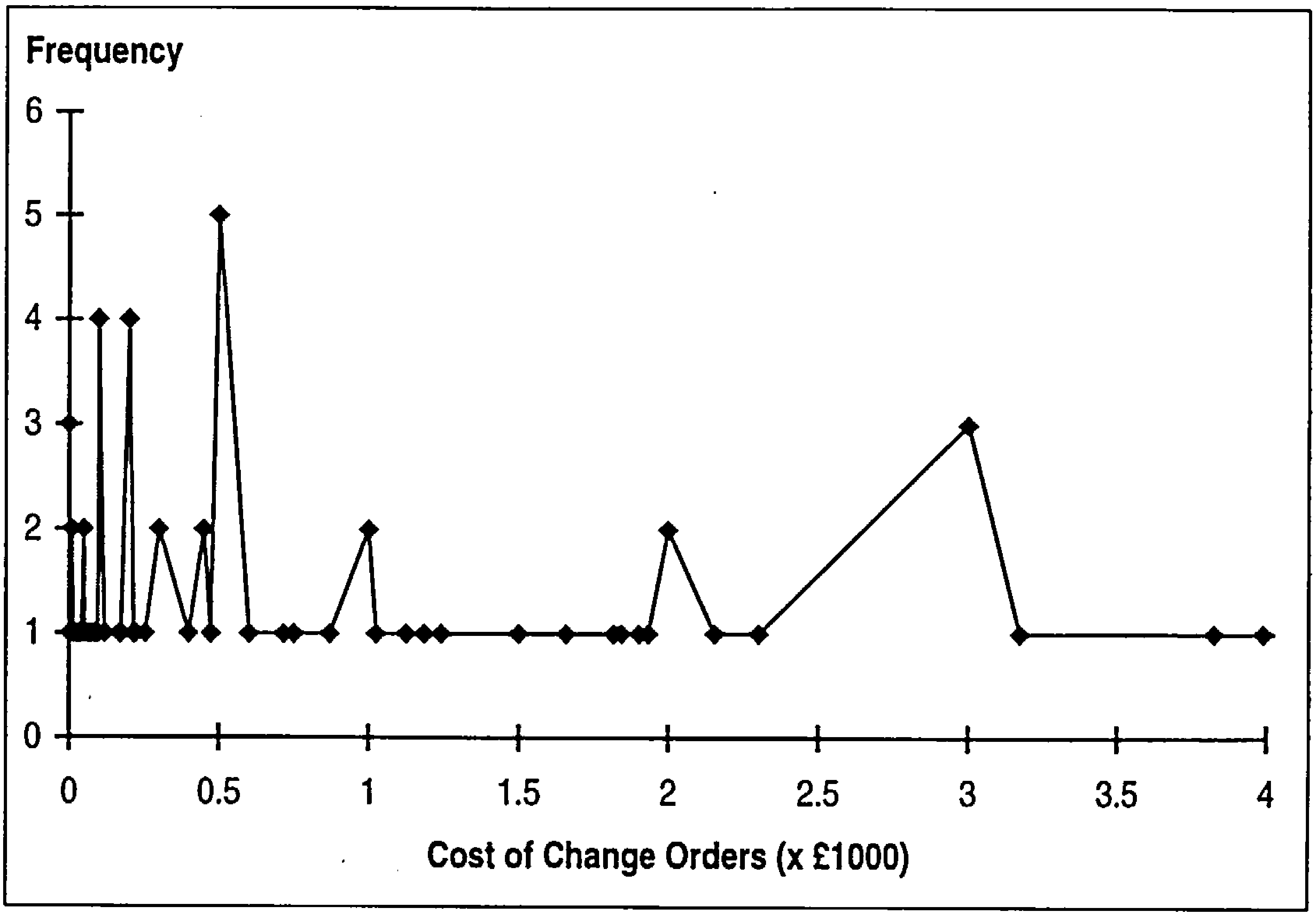


Figure D.6b – Change Order Cost Distribution: Raw Data (£0 to £4000)

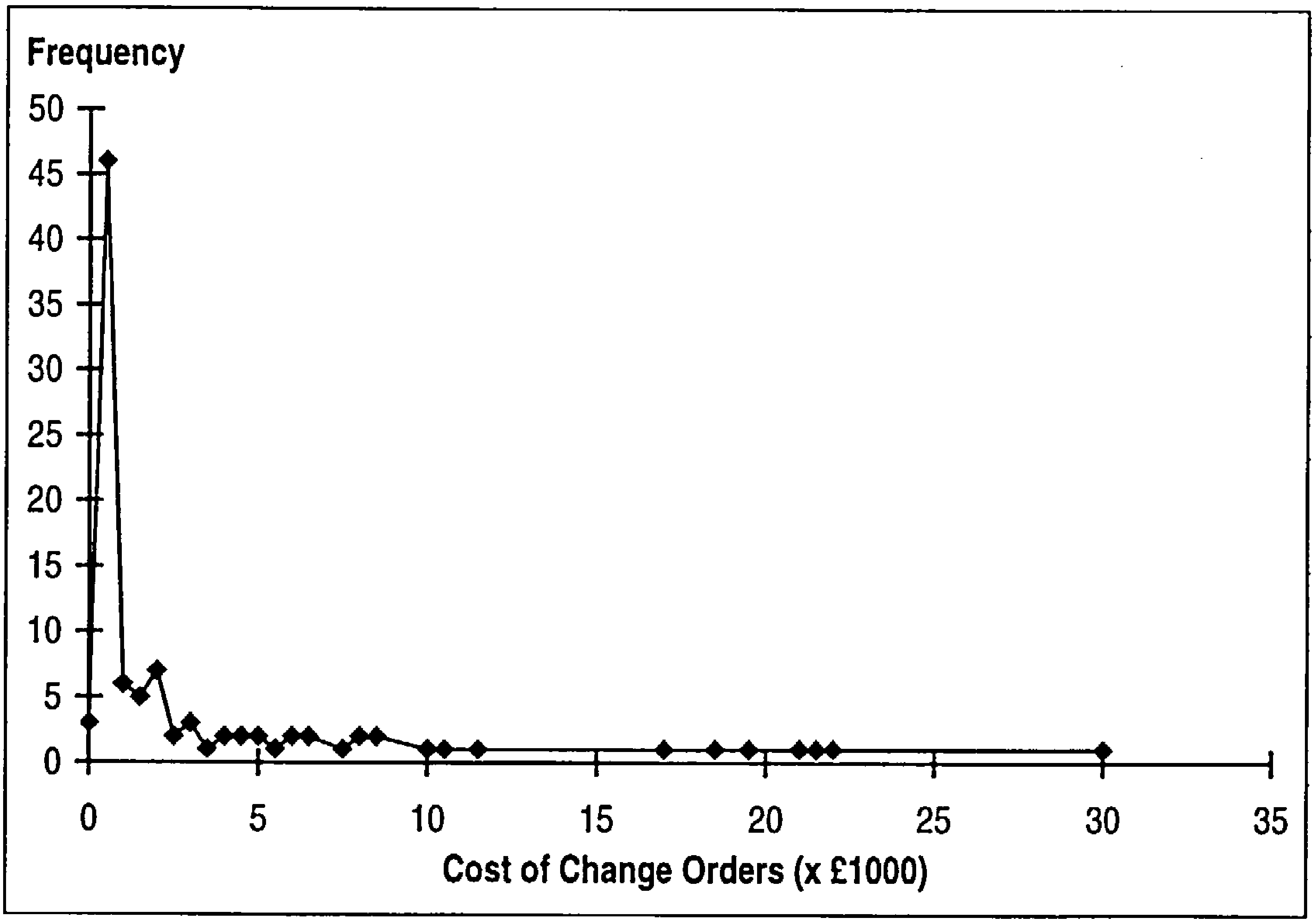


Figure D.7 – Distribution of Change Order Costs: Cost Class Intervals of £500

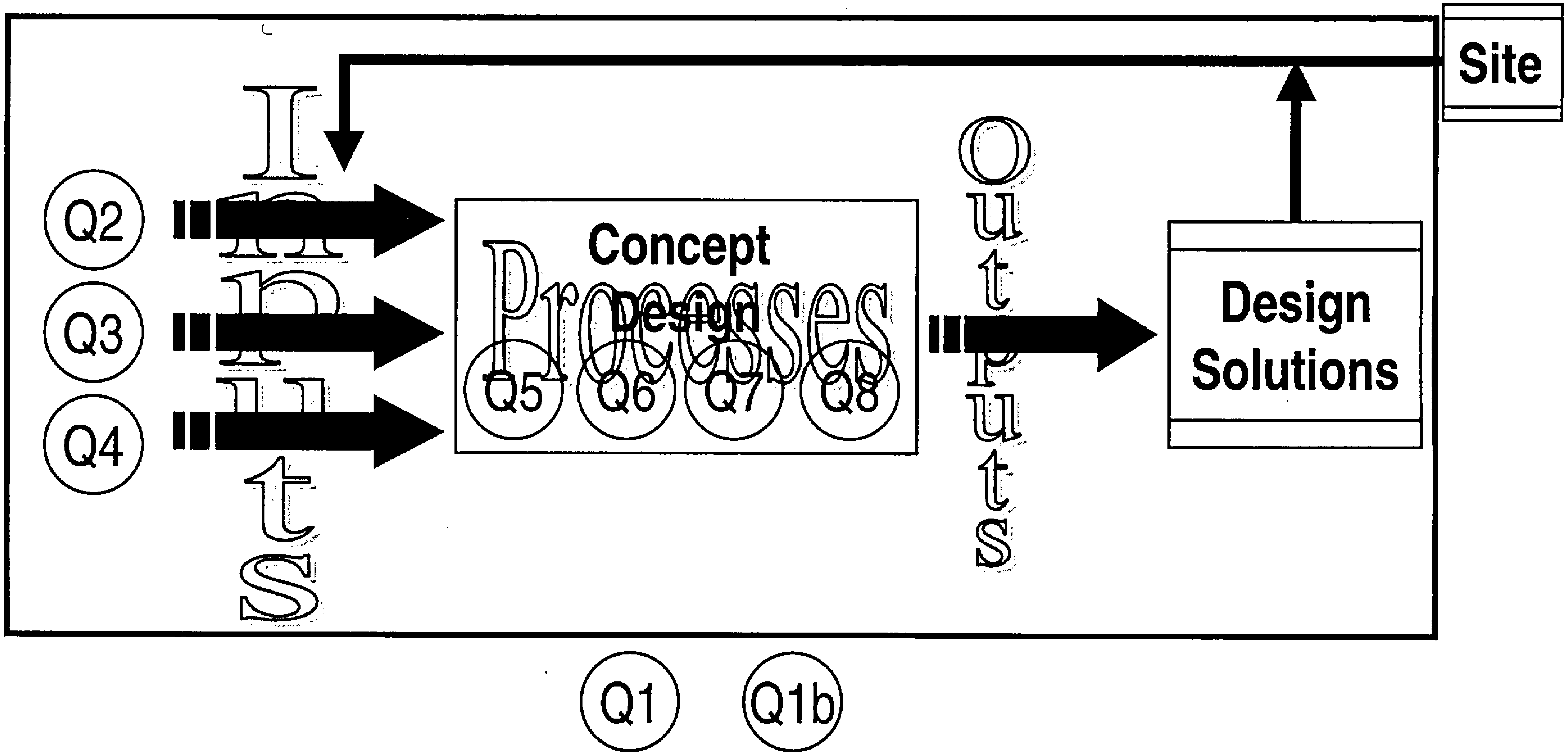
[BLANK PAGE]

APPENDIX E

Analysis of Interviews Conducted at Stanley Bragg Partnership Ltd and Foster and Partners

- Interview Questions
- Main Themes Identified

Overview of Questions



Interview Questions (1 - 4)

1. What effects the development of a concept design the most, the individual architect who has been assigned the task of producing the concept or the framework in which he/she works?

1b. Can you give me a brief outline of the design process as you see it from the inception of the project until the construction phase takes place? [Stanley Bragg only]

2. Can you explain the briefing process, please?

3. What information is gathered to support the brief and assess its feasibility?

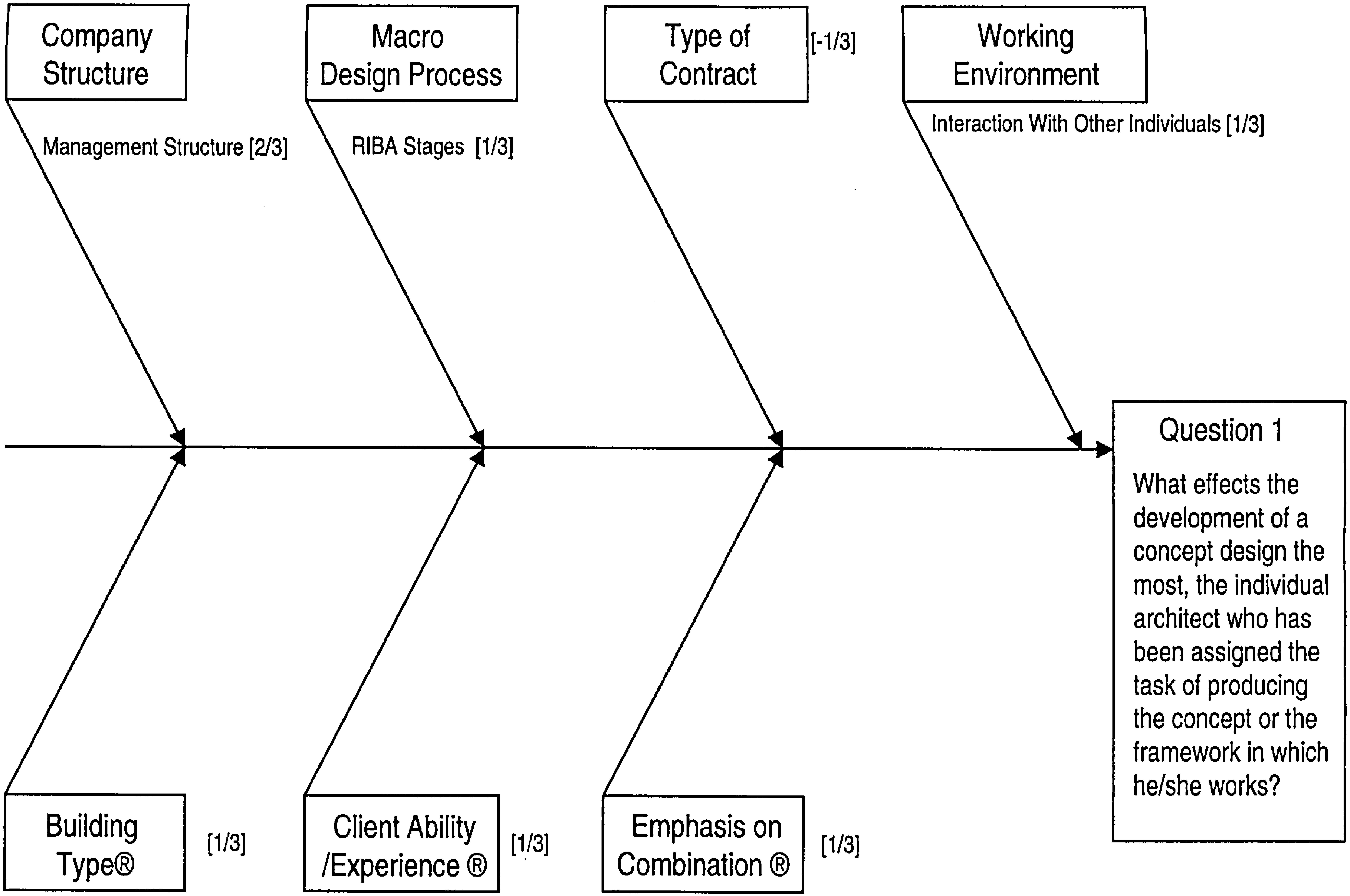
4. Do you define important parameters / factors which need to be considered in design solutions?

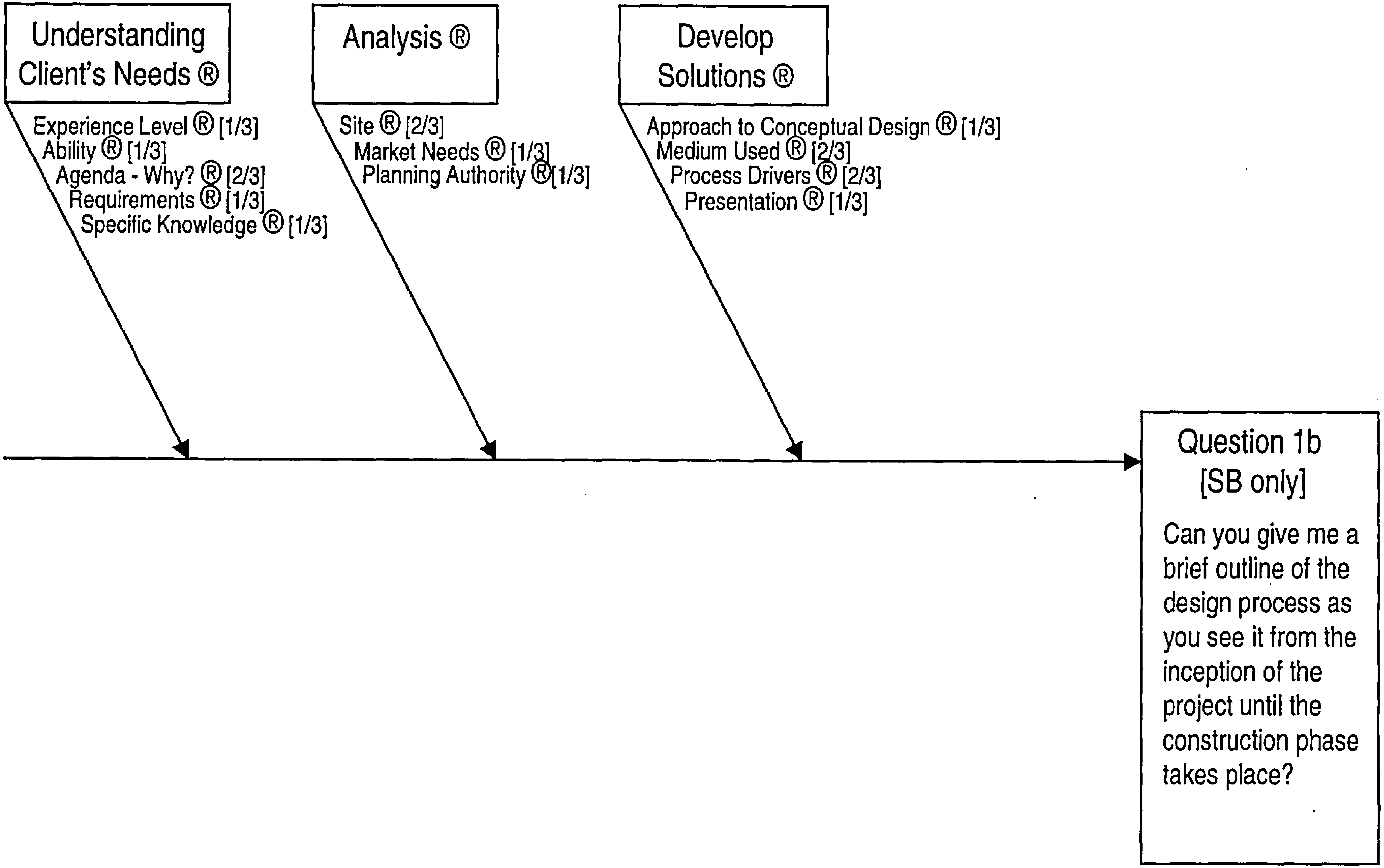
Interview Questions (5 - 9)

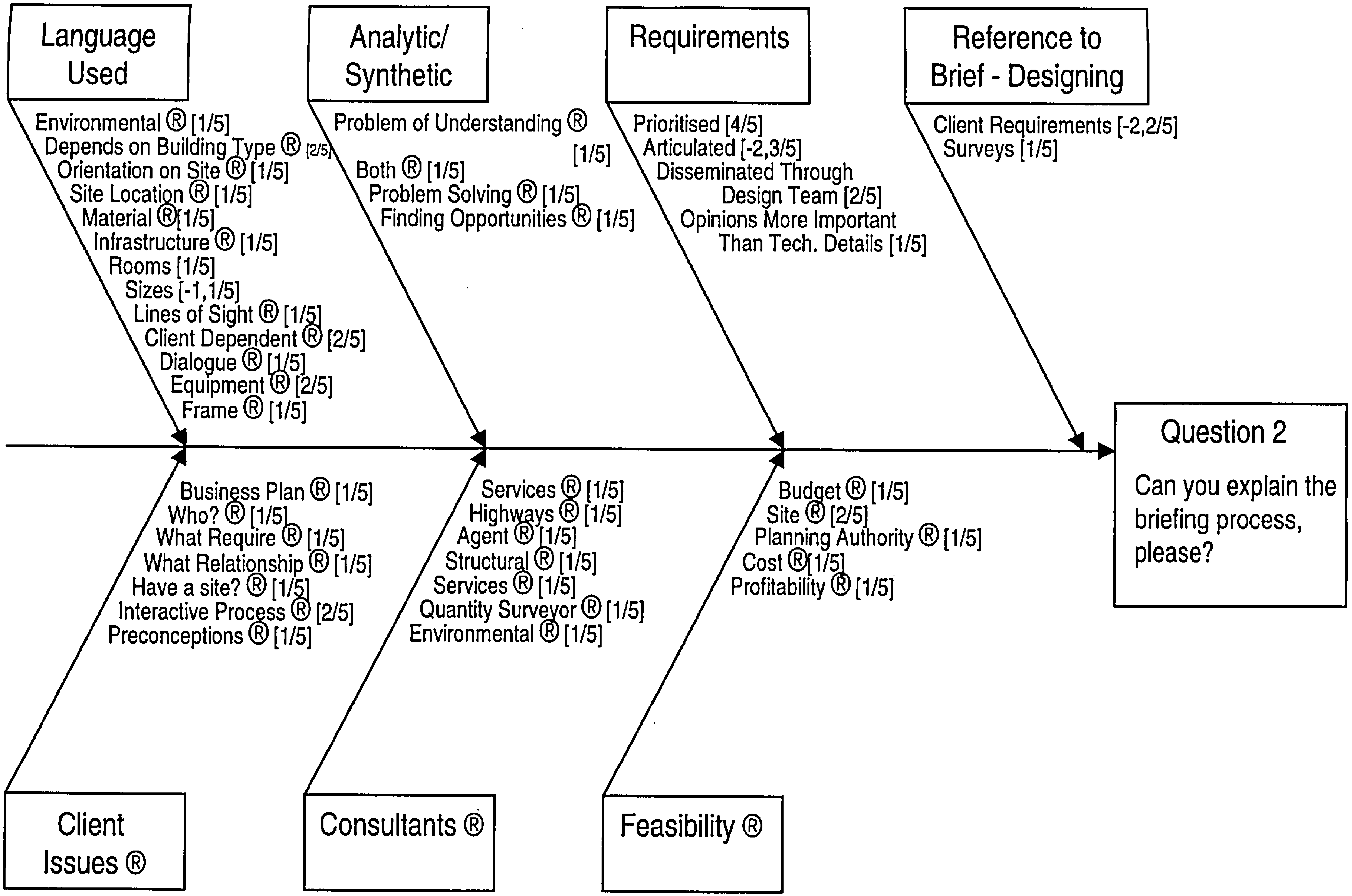
5. Having now developed a comprehensive understanding of the brief (and hence the client's needs) and some of the important constraints involved, how do you go about translating that into a conceptual design?
6. How do you work in the concept stage?
7. Do you consider such factors as cost implications, assembly and construction techniques in the conceptual design stage?
8. Is it typical to follow the RIBA guidelines for every project? [Foster and Partners only]
9. What problems typically occur on site that are directly related to the design? [Foster and Partners only]

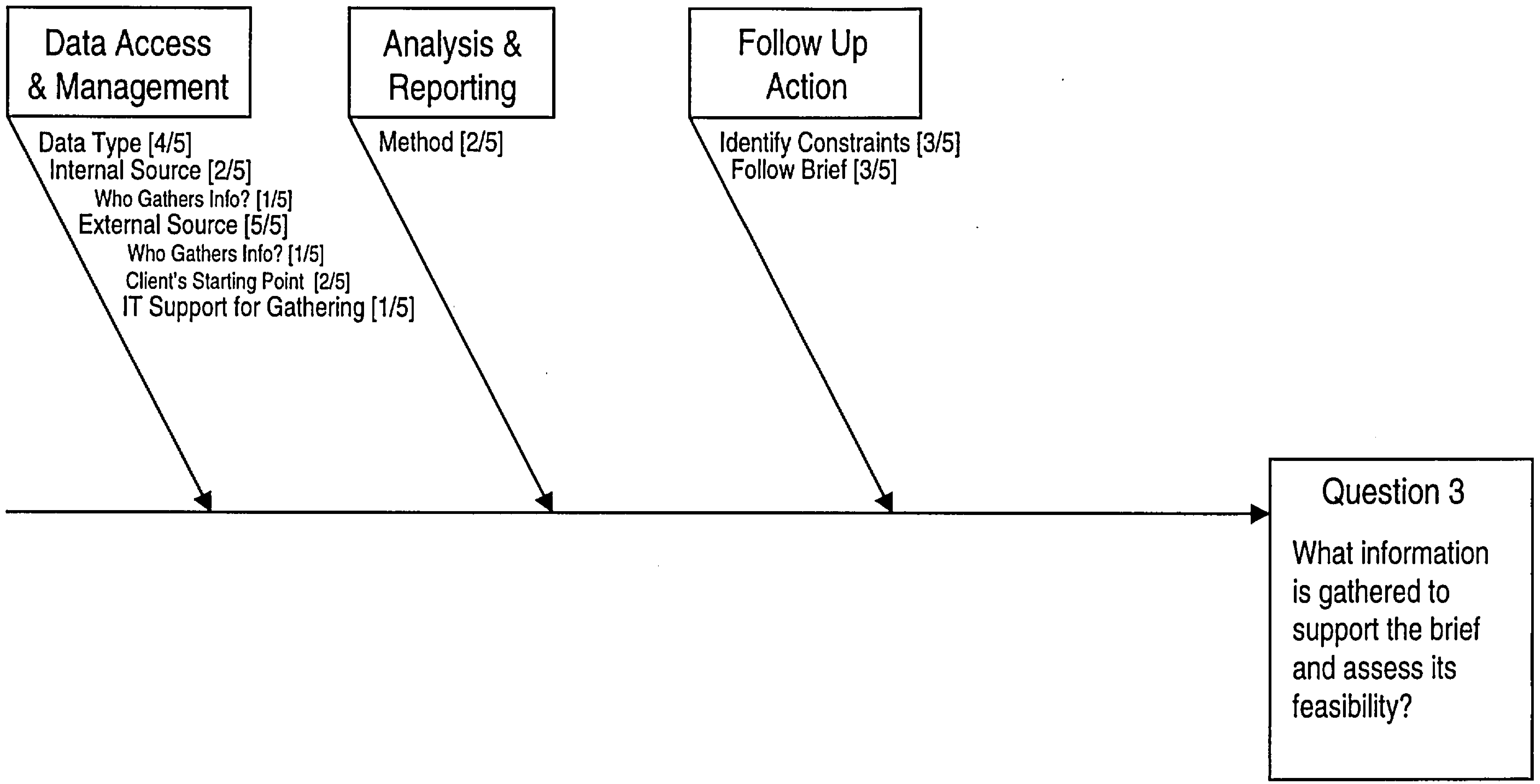
Key to Diagrams

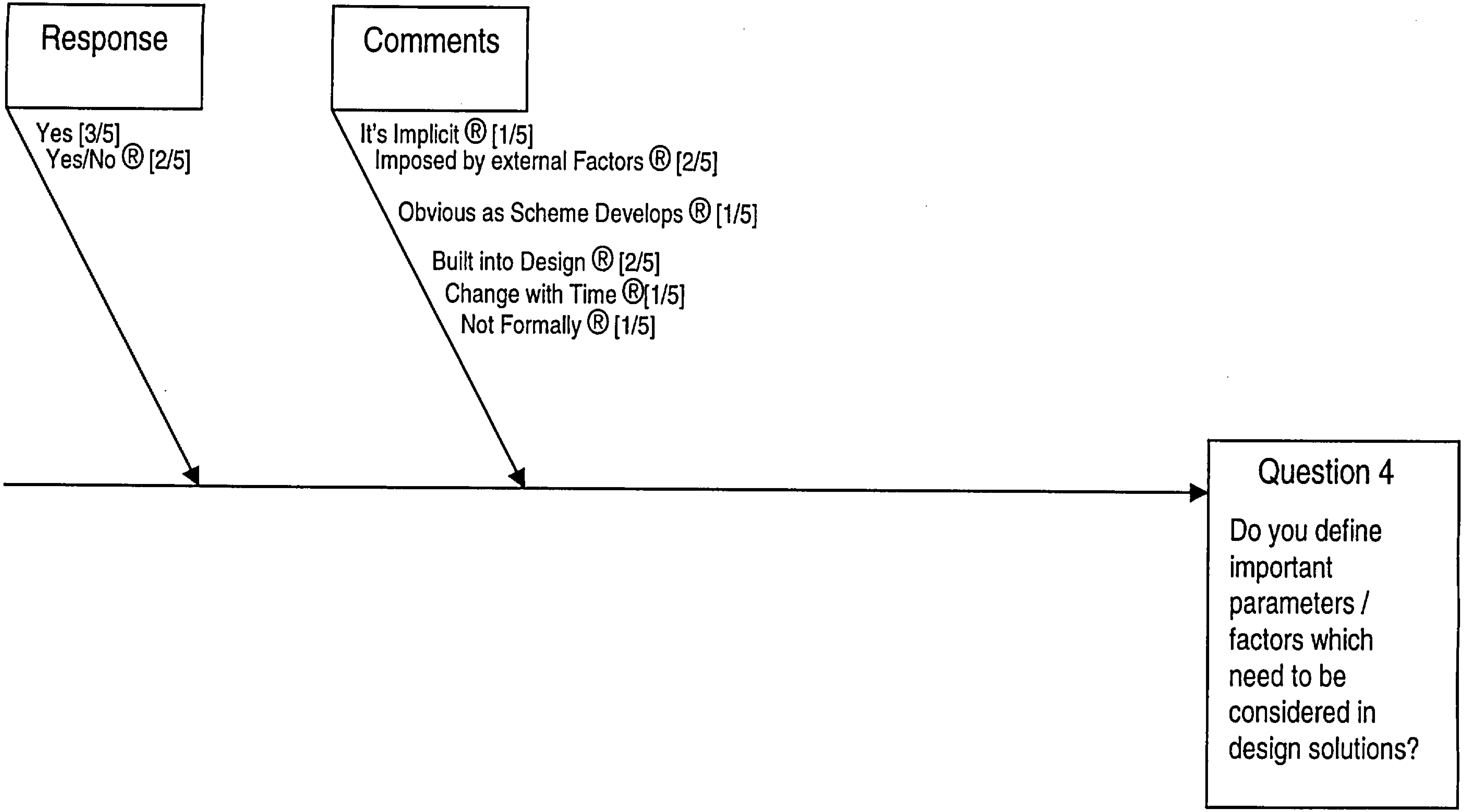
- Words/Phrases/Lines in Red ® - **Un**planned Question or Response
- Words/Phrases/Lines in Blue - Planned Question or Response
- Words/Phrases/Lines in Black - Retrospective Structure
- [2/5] - Two Out of the Five People Asked Mentioned this Point/Positive Response
- [-1/3] - One Out of the Three People Asked Responded Negatively to this Point


Company Structure
Management Structure [2/3]
Macro Design Process
RIBA Stages [1/3]
Type of Contract
[-1/3]
Working Environment
Interaction With Other Individuals [1/3]
Question 1
What effects the development of a concept design the most, the individual architect who has been assigned the task of producing the concept or the framework in which he/she works?
Building Type®
[1/3]
Client Ability /Experience ®
[1/3]
Emphasis on Combination ®
[1/3]


Understanding Client's Needs ®
Experience Level ® [1/3]
Ability ® [1/3]
Agenda - Why? ® [2/3]
Requirements ® [1/3]
Specific Knowledge ® [1/3]
Analysis ®
Site ® [2/3]
Market Needs ® [1/3]
Planning Authority ®[1/3]
Develop Solutions ®
Approach to Conceptual Design ® [1/3]
Medium Used ® [2/3]
Process Drivers ® [2/3]
Presentation ® [1/3]
Question 1b
[SB only]
Can you give me a brief outline of the design process as you see it from the inception of the project until the construction phase takes place?


Language Used
Environmental ® [1/5]
Depends on Building Type ® [2/5]
Orientation on Site ® [1/5]
Site Location ® [1/5]
Material ®[1/5]
Infrastructure ® [1/5]
Rooms [1/5]
Sizes [-1,1/5]
Lines of Sight ® [1/5]
Client Dependent ® [2/5]
Dialogue ® [1/5]
Equipment ® [2/5]
Frame ® [1/5]
Analytic/ Synthetic
Problem of Understanding ® [1/5]
Both ® [1/5]
Problem Solving ® [1/5]
Finding Opportunities ® [1/5]
Requirements
Prioritised [4/5]
Articulated [-2,3/5]
Disseminated Through Design Team [2/5]
Opinions More Important Than Tech. Details [1/5]
Reference to Brief - Designing
Client Requirements [-2,2/5]
Surveys [1/5]
Question 2
Can you explain the briefing process, please?
Business Plan ® [1/5]
Who? ® [1/5]
What Require ® [1/5]
What Relationship ® [1/5]
Have a site? ® [1/5]
Interactive Process ® [2/5]
Preconceptions ® [1/5]
Client Issues ®
Services ® [1/5]
Highways ® [1/5]
Agent ® [1/5]
Structural ® [1/5]
Services ® [1/5]
Quantity Surveyor ® [1/5]
Environmental ® [1/5]
Consultants ®
Budget ® [1/5]
Site ® [2/5]
Planning Authority ® [1/5]
Cost ®[1/5]
Profitability ® [1/5]
Feasibility ®


Data Access & Management
Data Type [4/5]
Internal Source [2/5]
Who Gathers Info? [1/5]
External Source [5/5]
Who Gathers Info? [1/5]
Client's Starting Point [2/5]
IT Support for Gathering [1/5]
Analysis & Reporting
Method [2/5]
Follow Up Action
Identify Constraints [3/5]
Follow Brief [3/5]
Question 3
What information is gathered to support the brief and assess its feasibility?



Response

Yes [3/5]
Yes/No ® [2/5]

Comments

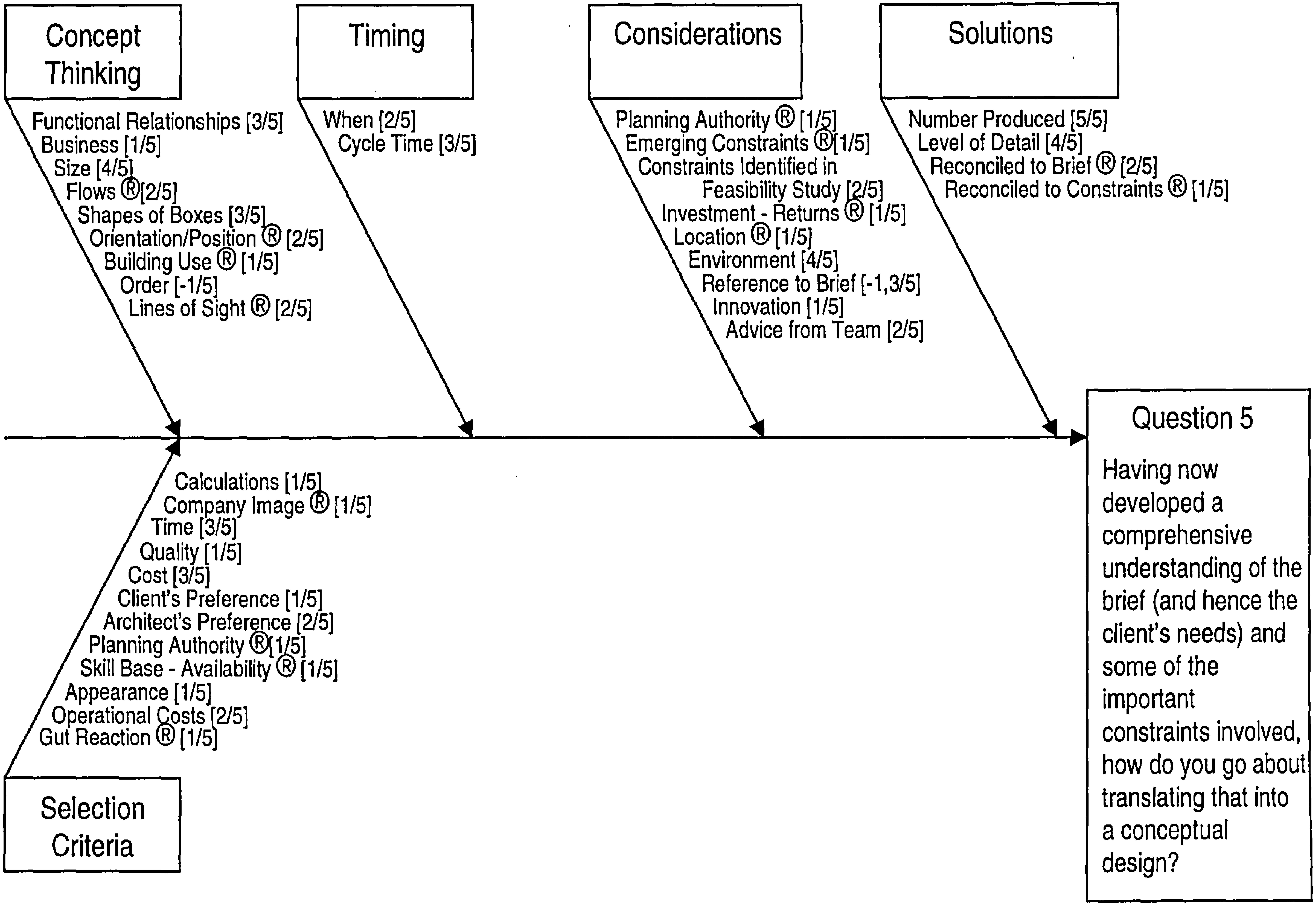
It's Implicit ® [1/5]
Imposed by external Factors ® [2/5]

Obvious as Scheme Develops ® [1/5]

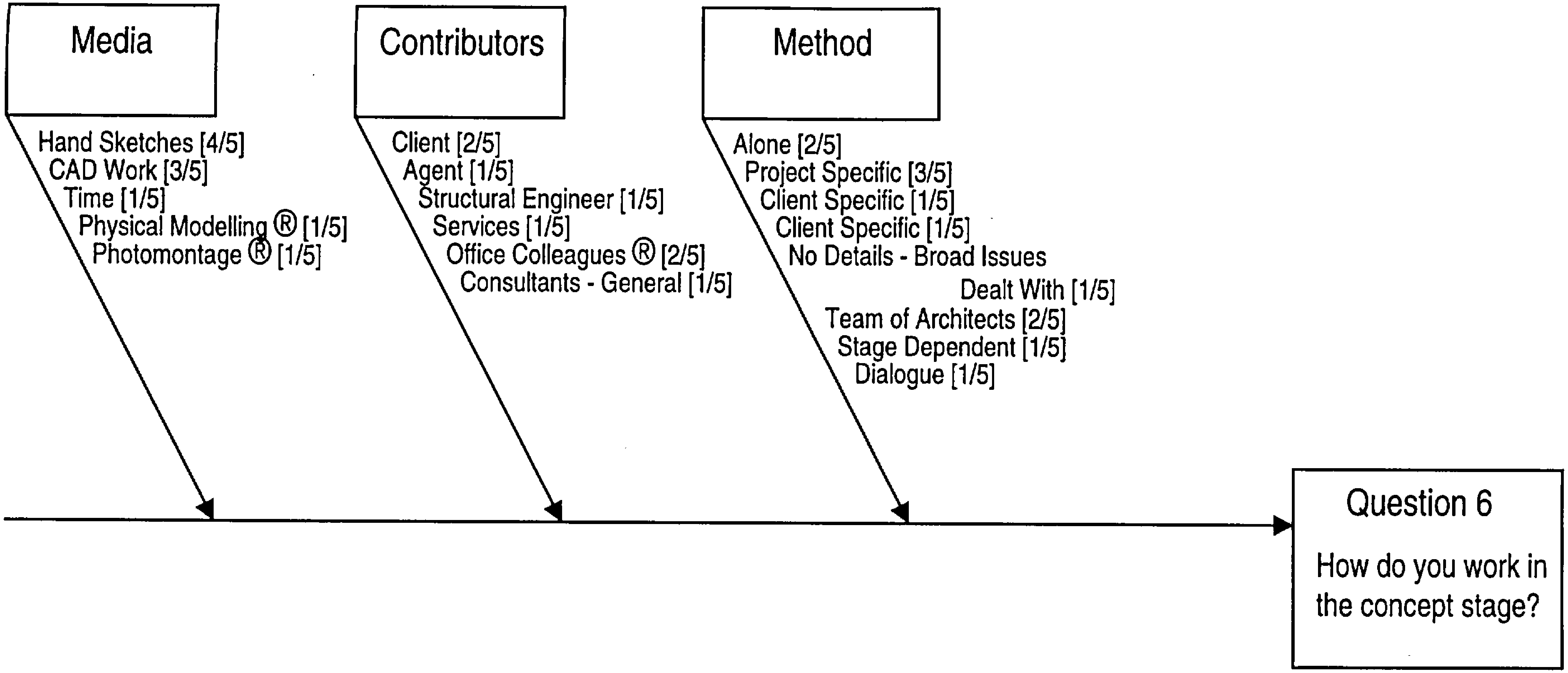
Built into Design ® [2/5]
Change with Time ®[1/5]
Not Formally ® [1/5]

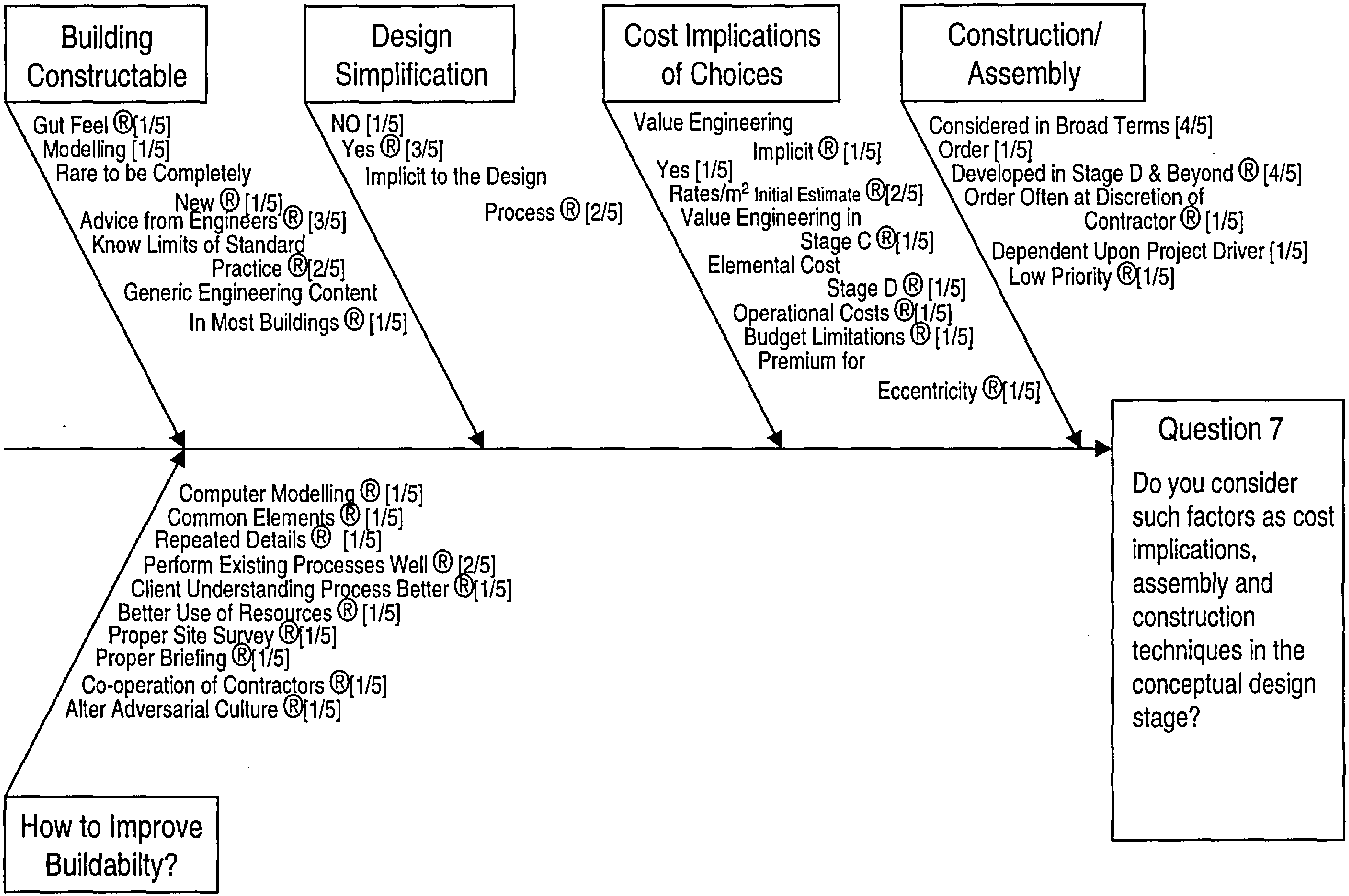
Question 4

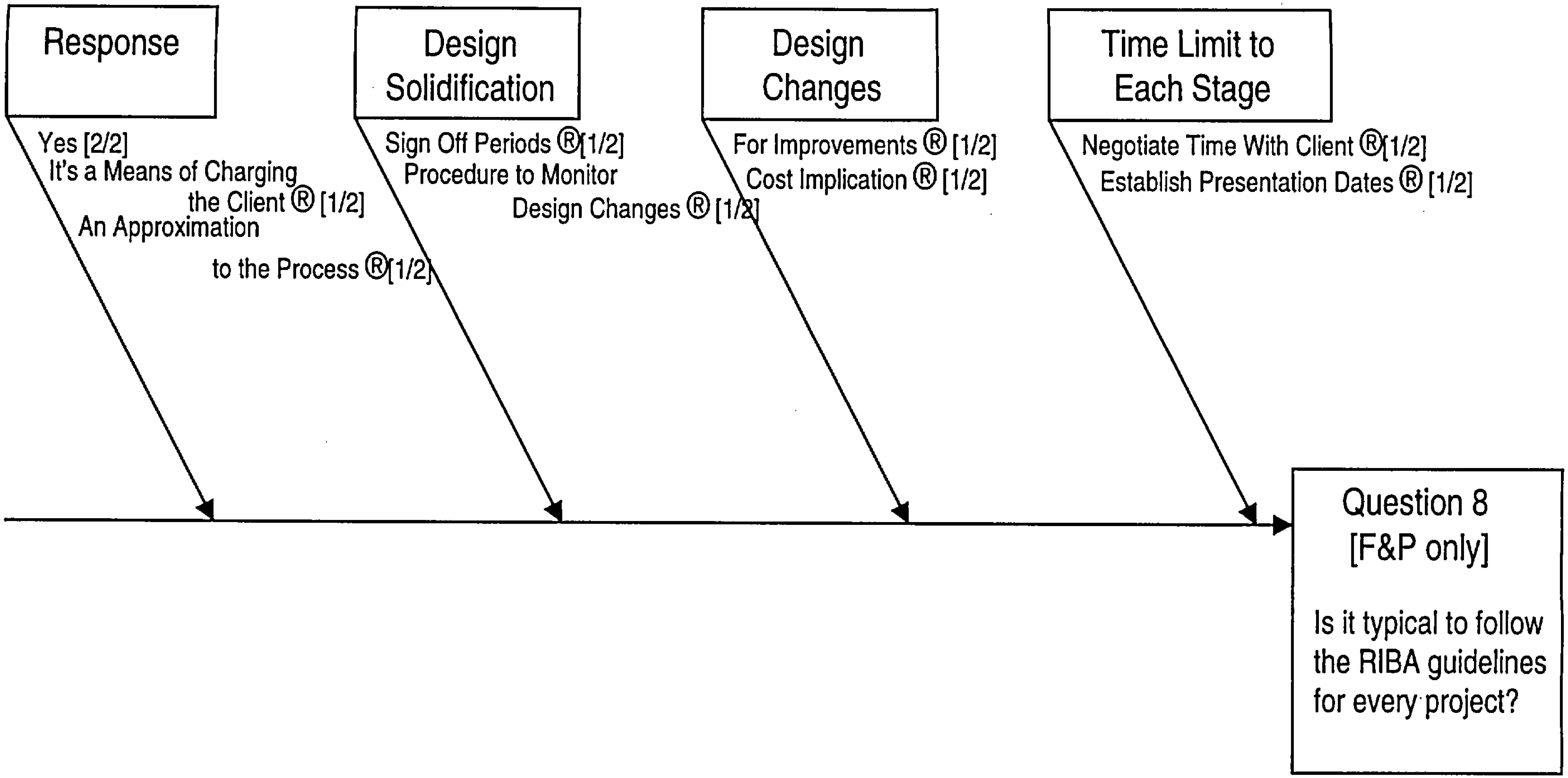
Do you define important parameters / factors which need to be considered in design solutions?



Having now developed a comprehensive understanding of the brief (and hence the client's needs) and some of the important constraints involved, how do you go about translating that into a conceptual design?


Media
Hand Sketches [4/5]
CAD Work [3/5]
Time [1/5]
Physical Modelling ® [1/5]
Photomontage ® [1/5]
Contributors
Client [2/5]
Agent [1/5]
Structural Engineer [1/5]
Services [1/5]
Office Colleagues ® [2/5]
Consultants - General [1/5]
Method
Alone [2/5]
Project Specific [3/5]
Client Specific [1/5]
Client Specific [1/5]
No Details - Broad Issues Dealt With [1/5]
Team of Architects [2/5]
Stage Dependent [1/5]
Dialogue [1/5]
Question 6
How do you work in the concept stage?


Building Constructable
Gut Feel ®[1/5]
Modelling [1/5]
Rare to be Completely New ® [1/5]
Advice from Engineers ® [3/5]
Know Limits of Standard Practice ®[2/5]
Generic Engineering Content In Most Buildings ® [1/5]
Design Simplification
NO [1/5]
Yes ® [3/5]
Implicit to the Design Process ® [2/5]
Cost Implications of Choices
Value Engineering Implicit ® [1/5]
Yes [1/5]
Rates/m² Initial Estimate ®[2/5]
Value Engineering in Stage C ®[1/5]
Elemental Cost Stage D ® [1/5]
Operational Costs ®[1/5]
Budget Limitations ® [1/5]
Premium for Eccentricity ®[1/5]
Construction/ Assembly
Considered in Broad Terms [4/5]
Order [1/5]
Developed in Stage D & Beyond ® [4/5]
Order Often at Discretion of Contractor ® [1/5]
Dependent Upon Project Driver [1/5]
Low Priority ®[1/5]
How to Improve Buildabilty?
Computer Modelling ® [1/5]
Common Elements ® [1/5]
Repeated Details ® [1/5]
Perform Existing Processes Well ® [2/5]
Client Understanding Process Better ®[1/5]
Better Use of Resources ® [1/5]
Proper Site Survey ®[1/5]
Proper Briefing ®[1/5]
Co-operation of Contractors ®[1/5]
Alter Adversarial Culture ®[1/5]
Question 7
Do you consider such factors as cost implications, assembly and construction techniques in the conceptual design stage?



Response

Yes [2/2]
It's a Means of Charging the Client ® [1/2]
An Approximation to the Process ®[1/2]

Design Solidification

Sign Off Periods ®[1/2]
Procedure to Monitor Design Changes ® [1/2]

Design Changes

For Improvements ® [1/2]
Cost Implication ® [1/2]

Time Limit to Each Stage

Negotiate Time With Client ®[1/2]
Establish Presentation Dates ® [1/2]

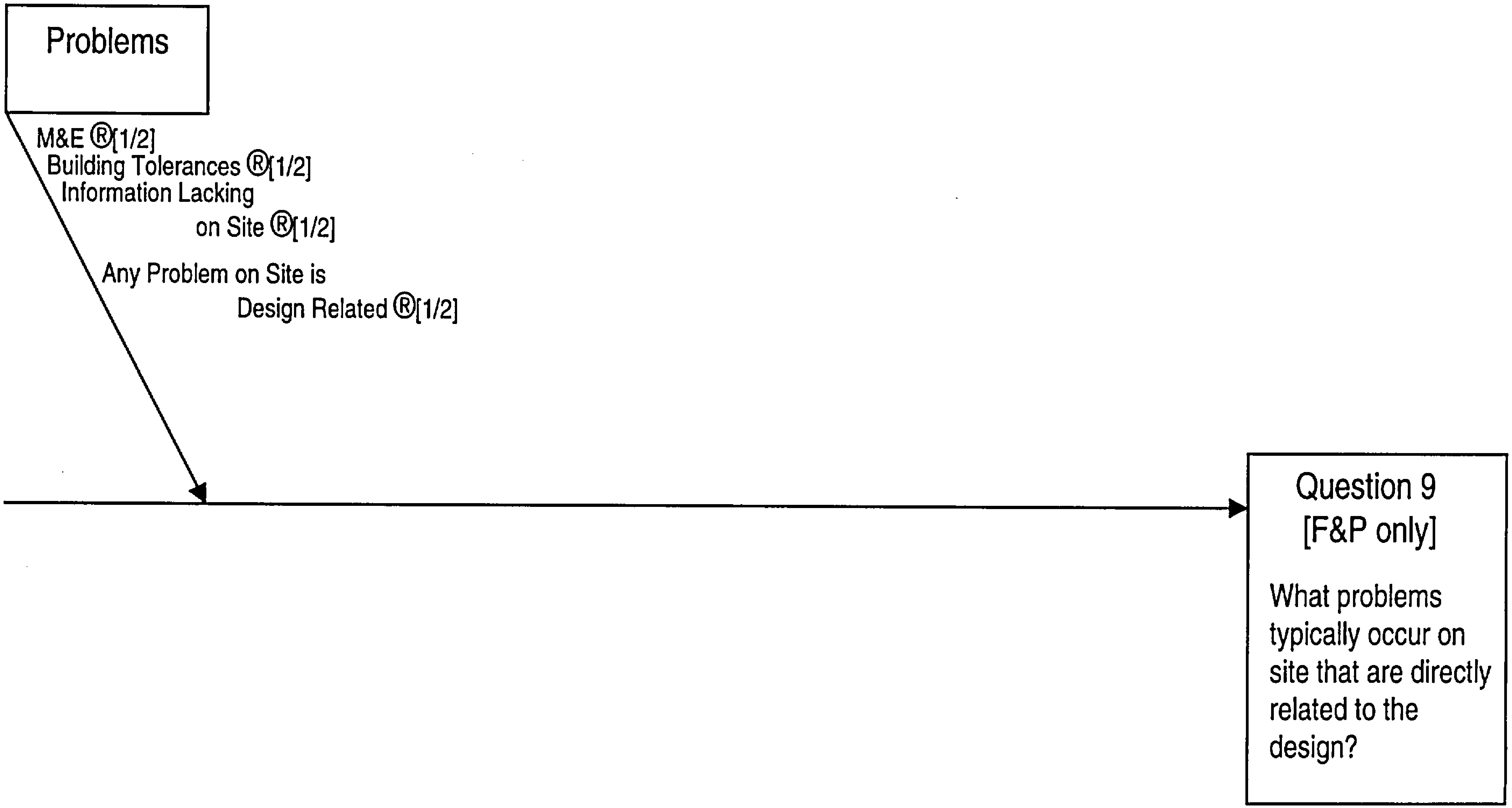
Question 8
[F&P only]

Is it typical to follow the RIBA guidelines for every project?

Tool Implementation Factors

{Full Data Set}

- Computer/Paper Based
  - 5 Preferred Computers, 5 Preferred Paper
  - Everybody has access to computers
- Time/Frequency
  - Concise - minimise time
  - Frequency from Daily - Monthly
  - Disagreement over identifying " important design decisions"
- Comments
  - Could be used as a QA tool
  - Foresee implementation problems - discipline of completing the template
  - Template needs to be reconciled to each stage of the project
  - Must define clearly who is responsible for completing the template
- Comments
  - Should be category based - not much writing
  - Wary of additional work load


Problems
M&E ®[1/2]
Building Tolerances ®[1/2]
Information Lacking on Site ®[1/2]
Any Problem on Site is Design Related ®[1/2]
Question 9
[F&P only]
What problems typically occur on site that are directly related to the design?

[BLANK PAGE]

APPENDIX F

List of Tables

Table F.1 – Building Details and Construction Planning Outline for the Case Studies Used in Design Decision Process Maps 2
Table F.2 – Design Features for the Case Studies Used in Design Decision Process Maps 3
Table F.3 – Client Assessment for the Case Studies Used in Design Decision Process Maps...... 4
Table F.4 – Design Stage Dates for the Case Studies Used in Design Decision Process Maps ... 5

Building Details

Name of Building		15 - 18 High Street Chelmsford	South Terminal IDL Gatwick	Exeter Street Bourne
Project Type		Refurbishment / Construction	Extension of existing facility	Construction
Building Type		Retail	Retail/operational areas (sitting, transfers)	Supermarket
Location		Chelmsford, Essex	Gatwick Airport	Bourne, Lincolnshire
Floor Area		3000 m^2	3066m^2	2356m^2
Height		12m	20m	7.5m
No. of Storeys		2	5	1
Type of Construction	**Brick**	Yes		Yes
	Steel Frame	Yes	Yes	Yes
	Concrete Frame			Concrete around some of steel frame
	Cladding		Yes - steel panel with glass	
	Roof Type	Slate	Aluminium sheet roof	Profile steel
	Distinctive Features	Retained Listed Building Range		Main entrance

Construction Planning

Type of Contract		JCT 80 Measured with Quantities	BAA specific based on New Engineering Contract - multi contractor version (with suppliers)	Design and Build
Length of Phase	**Planned Construction**	9 months	22 months	6 months
	Pre-eng.	Steel frame components fabricated off site during contract	Pre-formed service modules - piping, duct work, cables	Steel frame (arrives on site as a kit ready for construction) Windows - units made up railing features for boundary wall, all the soffits, eaves, and faciaes for roof prefabricated, painted off site
No. of Contractors		1 main contractor, 4 subcontractors		1 main contractor, 20 subcontractors
No. of Work Packages		5		17

Table F.1 – Building Details and Construction Planning Outline for the Case Studies Used in Design Decision Process Maps

Design Features

Level of Innovation	**Design**	Medium	Medium	Medium
	Materials	Low	High	Medium
	Assembly	Low	High	Medium
			High - people on board, contributions to design, programme and cost implications, process mapping - selections made on basis of cost and programme after function	
Level of Architect Output from CAD to Main Contractor		High 80 %		Medium ~ 60% General Arrangements, production drawings, site layout and elevations, done on CAD Majority of design details are hand drawn

Table F.2 – Design Features for the Case Studies Used in Design Decision Process Maps

	Chelmsford	Gatwick	Bourne
Client Experience	High	High	High
Level Of Client Sophistication	High	High	High
Client Procured This Type Of Building Before?	Yes	Yes	Yes
Details	Multiple, 7 ongoing, 10s previously	One finished five years ago, a similar building is being constructed at the North Terminal	Multiple
Client A Repeat Client?	Yes	Yes	Yes
How Many Projects Done With Them Before?	2	10s within last ten years	Multiple till feasibility, not many completed buildings
What Design Management Contract Was Used?	RIBA – slight variation	BAA Framework Agreement	Not sure whether have a contract at the moment not sure whether it would be RIBA either. Flat fee for feasibility studies until the developer sells site to the end user.
Budget	£1.475 million – Shell and Core	Originally £20 million, with cost saving measures: £16.5 million	£1.5 million – Shell and Core £1.19 million - Fitout
Site Pre-Selected?	Yes	Yes	Yes

Table F.3 – Client Assessment for the Case Studies Used in Design Decision Process Maps

	Chelmsford	Gatwick	Bourne
Date of inception	23/11/96	Start of Feasibility 12/2/98	1/3/96
Date of placing the contract	15/3/99	D_2 Day (Equivalent) 25/11/98	5/11/98
Stage A-B	23/11/96 – 15/9/97	Inception is an internal client process (Feasibility) 12/2/98 – 5/5/98	1/3/96 – 6/10/97
Stage C	5/7/97 – 5/2/98	5/5/98 – 26/8/98	4/9/96 – 6/10/97 End User *4/3/98 – 4/5/98
Stage D	5/7/97 – 5/2/98	26/8/98 – D_1 Day 16/9/98 D_2 Day – 25/11/98	3/5/97 - 6/10/97 End User **30/10/98 – 23/12/98
Stage E	5/11/97 – 5/2/98		2/9/98 – 4/12/98
Stage F	5/11/97 – 23/4/98		2/9/98 – On going
Stage G	5/5/98 – On going		2/9/98 – On going
Outline Planning			6/10/97
Detailed Planning	23/11/97	July / August 1999	
Planning for Reserved Matters			30/10/98 Also resubmissions for minor changes to scheme

Table F.4 – Design Stage Dates for the Case Studies Used in Design Decision Process Maps

[BLANK PAGE]

APPENDIX G

List of Figures

Figure G.1 - Cumulative Count of Design Decisions Made Against Normalised Time (Chelmsford) 6
Figure G.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) - Chelmsford 6
Figure G.3 - Distribution of Design Decisions (Groups of 0.05 Normalised Time) - Chelmsford 7
Figure G.4 – Who Made the Design Decisions (Chelmsford) 19
Figure G.5 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Chelmsford) 19
Figure G.7 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Chelmsford) 20
Figure G.8 – Designer's Cost Visibility (Chelmsford) 24
Figure G.9 – The Types of Meetings Where Design Decisions Were Made (Chelmsford) 24
Figure G.10 – Percentage of Design Decisions Using Particular Information Source Types (Chelmsford) 25
Figure G.11 – Percentage of Design Decisions Using Particular Information Technology Types (Chelmsford) 25
Figure G.12 – Percentage of Design Decisions Occurring in Each RIBA Stage (Chelmsford) 26

List of Tables

Table G.1 – List of System / Sub-System Level Design Decisions for the Chelmsford Case Study by Order of Decision Occurrence 5

Table G.2 – Design Team (Chelmsford) 8

Table G.3 – When Each Design Team Member Joined the Project (Chelmsford) 8

Table G.4 – List of System / Sub-System Level Design Decisions for the Chelmsford Case Study by Order of Decision Maker 11

Table G.5 - List of System / Sub-System Level Design Decisions that the Architect was Involved in Making (Chelmsford) 12

Table G.6 - List of System / Sub-System Level Design Decisions that the Client was Involved in Making (Chelmsford) 13

Table G.7 - List of System / Sub-System Level Design Decisions that the Client's Agent was Involved in Making (Chelmsford) 14

Table G.8 - List of System / Sub-System Level Design Decisions that the End User was Involved in Making (Chelmsford) 14

Table G.9 - List of System / Sub-System Level Design Decisions that the Legal Consultant was Involved in Making (Chelmsford) 14

Table G.10 - List of System / Sub-System Level Design Decisions that the Planning Authority was Involved in Making (Chelmsford) 15

Table G.11 - List of System / Sub-System Level Design Decisions that the Planning Supervisor was Involved in Making (Chelmsford) 15

Table G.12 - List of System / Sub-System Level Design Decisions that the Project Manager was Involved in Making (Chelmsford) 16

Table G.13 - List of System / Sub-System Level Design Decisions that the Quantity Surveyor was Involved in Making (Chelmsford) 17

Table G.14 - List of System / Sub-System Level Design Decisions that Specialist Consultants were Involved in Making (Chelmsford) 17

Table G.15 - List of System / Sub-System Level Design Decisions that the Structural Engineer was Involved in Making (Chelmsford) 18

Table G.16 - List of System / Sub-System Level Design Decisions with Corresponding 'Constraint' and 'Reasons For Selection' Categories Cited (Chelmsford) 23

Decision Maker	Decision Number	Decision Order	Chelmsford Design Decision Made	Normalised Time
Architect - C	79	1	To incorporate a lift shaft into the scheme	-0.0080092
Architect - C	93	2	Extent of demolition on site	0.08352403
Client (Developer) - B	18	3	Footprint/form of scheme	0.20823799
Client (Developer) - B	35	4	Number of units and their size for the phase 1 development (high street)	0.21395881
Client (Developer) - B	54	5	Selection of system for external skin of new build	0.23684211
Client (Developer)	31	6	Choice of roofing material	0.24256293
Client (Developer) - B	34	7	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)	0.32265446
Structural Engineer	22	8	Configuration / Layout of the structure	0.34553776
Client (Developer)	36	9	Size and shape of unit 1	0.35469108
Client (Developer)	37	10	**Size and shape of unit 2**	**0.35469108**
Client (Developer)	39	11	Organisational layout of unit 1	0.35583524
Client (Developer)	40	12	Organisational layout of unit 2	0.35583524
Client (Developer)	81	13	Position of the lift shafts	0.36613272
Architect	32	14	Decide how to interface the new build roof with the existing listed building	0.36842105
Architect	29	15	**Configuration of roof (roof form)**	**0.37643021**
Architect	23	16	Structural bay dimensions	0.38443936
Architect	27	17	**Selection of roof structure material**	**0.41418764**
Architect	49	18	Finish for ground and first level floors	0.41418764
Structural Engineer	19	19	Decide whether 'Ground Beams' are a requirement and if so type (substructure)	0.41418764
Structural Engineer	20	20	Selection of structural frame for new build	0.41418764
Structural Engineer	47	21	Selecting overall floor slab configuration	0.41418764
Structural Engineer	48	22	Floor slab configuration at ground level	0.41418764
Structural Engineer	51	23	Defined the flat roof structure configuration (units 1 and 2) - new build	0.41418764
Architect	95	24	Specification of floor levels	0.41647597
Structural Engineer	26	25	To Retain the existing foundations for the listed building	0.43707094
Architect	28	26	Selection of roof structure material	0.4382151
Architect	30	27	Configuration of roof (roof form)	0.4382151
Client (Developer)	61	28	Decision as to the scope of service provision by the land lord	0.4610984

Client (Developer)	**76**	29	Position of the access point for service vehicles	0.46910755
Architect	**77**	30	Position of service bays	0.46910755
Architect	**78**	31	Traffic routes within the site	0.46910755
Client (Developer) - B	**24**	32	Create a clear area beneath the listed building	0.47254005
Architect - C	**57**	33	Articulate the new build elevations with rendered panels inset within brickwork skin	0.47254005
Architect	**97**	34	Dimension between external skin (vertical cladding) and gridline	0.47482838
Client (Developer)	**85**	35	Parking position / layout	0.4771167
Architect	**90**	36	Windows configuration	0.47940503
Architect	**91**	37	Amount of glazing used in the scheme	0.47940503
Architect	**88**	38	Roof drainage system	0.50114416
Architect	**33**	39	The roofing material for the flat roof areas	0.50572082
Structural Engineer	**17**	40	Selection of substructure -type of foundation	0.50572082
Structural Engineer	**80**	41	The construction type for the lift shaft	0.51601831
Architect	**64**	42	Decision to route all the services together	0.5194508
Architect - B	**67**	43	The selection of the insulating material for the external skin	0.52745995
Architect - B	**68**	44	The selection of the insulating material for the roof	0.52745995
Architect	**50**	45	Finish for second level floor	0.54004577
Architect	**52**	46	Type of partition for dividing wall between unit 1 and unit 2 in the existing building	0.54919908
Architect	**53**	47	Type of partition for means of escape areas for units 1 and 2	0.54919908
Client (Developer) - B	**59**	48	The material selection for the external skin	0.55377574
Architect	**55**	49	**The material selection for the external skin**	**0.55377574**
Structural Engineer	**58**	50	Selection of the material for the internal masonry leaf of external skin (i.e. The internal skin)	0.55377574
Architect	**96**	51	Connection between vertical cladding (external skin) and floor slab	0.58581236
Architect	**75**	52	Decision to have smoke vents in the escape cores	0.58695652
Client (Developer)	**84**	53	Materials selection for the parking area	0.58695652
Architect	**74**	54	Type of fire protection for the steel frame	0.58810069
Architect	**82**	55	The construction type of the stairs	0.58924485
Architect	**56**	56	Selection of material for feature masonry on external skin	0.59153318
Architect	**63**	57	**Route of services (source, route and to - internal within building)**	**0.59153318**
Client (Developer) - B	**42**	58	**Public access doors to ginnel**	**0.60640732**
Architect	**41**	59	Specification of fire escape doors to the ginnel walk way	0.60640732
Architect	**44**	60	Specification of listed building internal doors	0.60640732
Architect	**45**	61	Specification of access door to listed building from flat roofs of each unit	0.60640732
Architect	**46**	62	Specification of internal means of escape doors (general)	0.60640732
Architect	**94**	63	Floor finish for the listed building areas	0.61327231
Client (Developer) - B	**43**	64	Public access doors to ginnel (change from aluminium in tender document to timber)	0.63043478
Architect	**2**	65	**Paving layout and materials to the ginnel**	**0.63157895**

Architect	6	66	**Paving layout and materials to the ginnel (two more options)**	**0.63157895**
Architect	83	67	Paving layout and materials to the ginnel	0.63157895
Client (Developer)	89	68	Windows materials / system type	0.65217391
Architect	21	69	Bracing to steel frame	0.67505721
Client (Developer)	8	70	Selection of external light fittings to the ginnel	0.68764302
Architect	3	71	Selection of external lighting fitting	0.68764302
Architect	9	72	Specification of external lighting to covered front area of ginnel - beneath alley way	0.68764302
Client (Developer) - B	62	73	Route of services (source, route and to - internal within building)	0.69107551
Client (Developer) - B	7	74	Amendment of ginnel paving materials	0.69221968
Architect	16	75	Determine best position for statutory services meter cupboard	0.69565217
Client (Developer) - B	60	76	Design of external signage	0.701373
Architect	65	77	Redesigned the provision of electrical services	0.73684211
Client (Developer)	25	78	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)	0.76315789
Architect	66	79	Size and capacity of each service	0.79290618
Structural Engineer	86	80	To combine / separate foul and surface water drainage	0.81006865
Structural Engineer	87	81	Routes for foul and surface water drainage	0.81350114
Architect	69	82	The fire escape strategy for the 3rd floor of the listed building	0.81464531
Architect	70	83	Fire escape strategy for the second floors (new build and listed)	0.81464531
Architect	71	84	Fire escape strategy for the first floor (new build and listed) 17-18 High Street	0.81464531
Architect	72	85	Fire escape strategy for the ground floor (new build and listed)	0.81464531
Architect	73	86	Fire escape strategy for the first floor (new build and listed) 15-16 High Street	0.81464531
Architect	92	87	Location of internal and external plant areas	0.81578947
Client (Developer) - B	38	88	Re-design of the footprint of unit 2	0.82608696
Contractor	98	89	Method of installing piles (design rationalisation)	1

Table G.1 – List of System / Sub-System Level Design Decisions for the Chelmsford Case Study by Order of Decision Occurrence

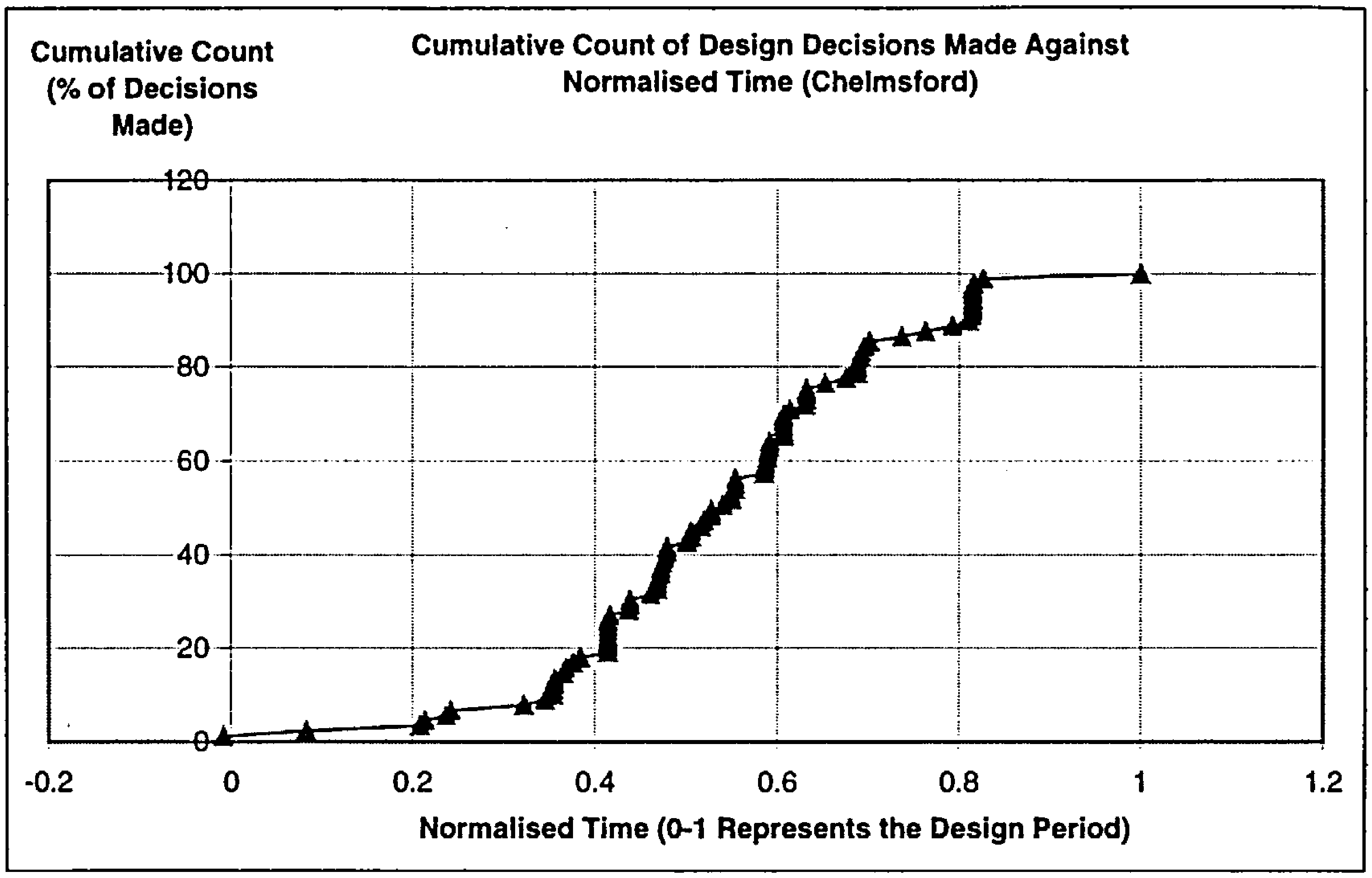


Figure G.1 - Cumulative Count of Design Decisions Made Against Normalised Time (Chelmsford)

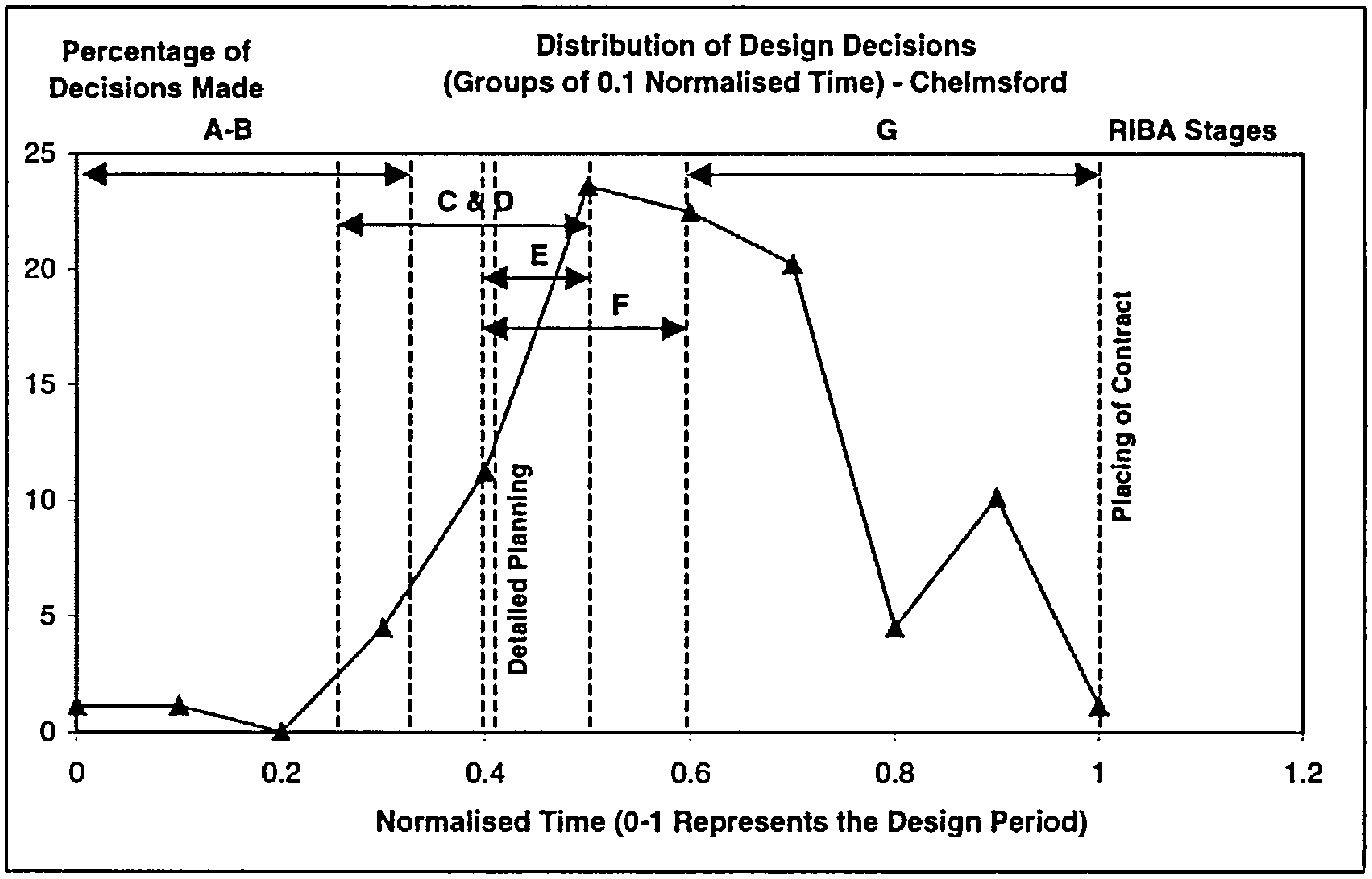


Figure G.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) - Chelmsford

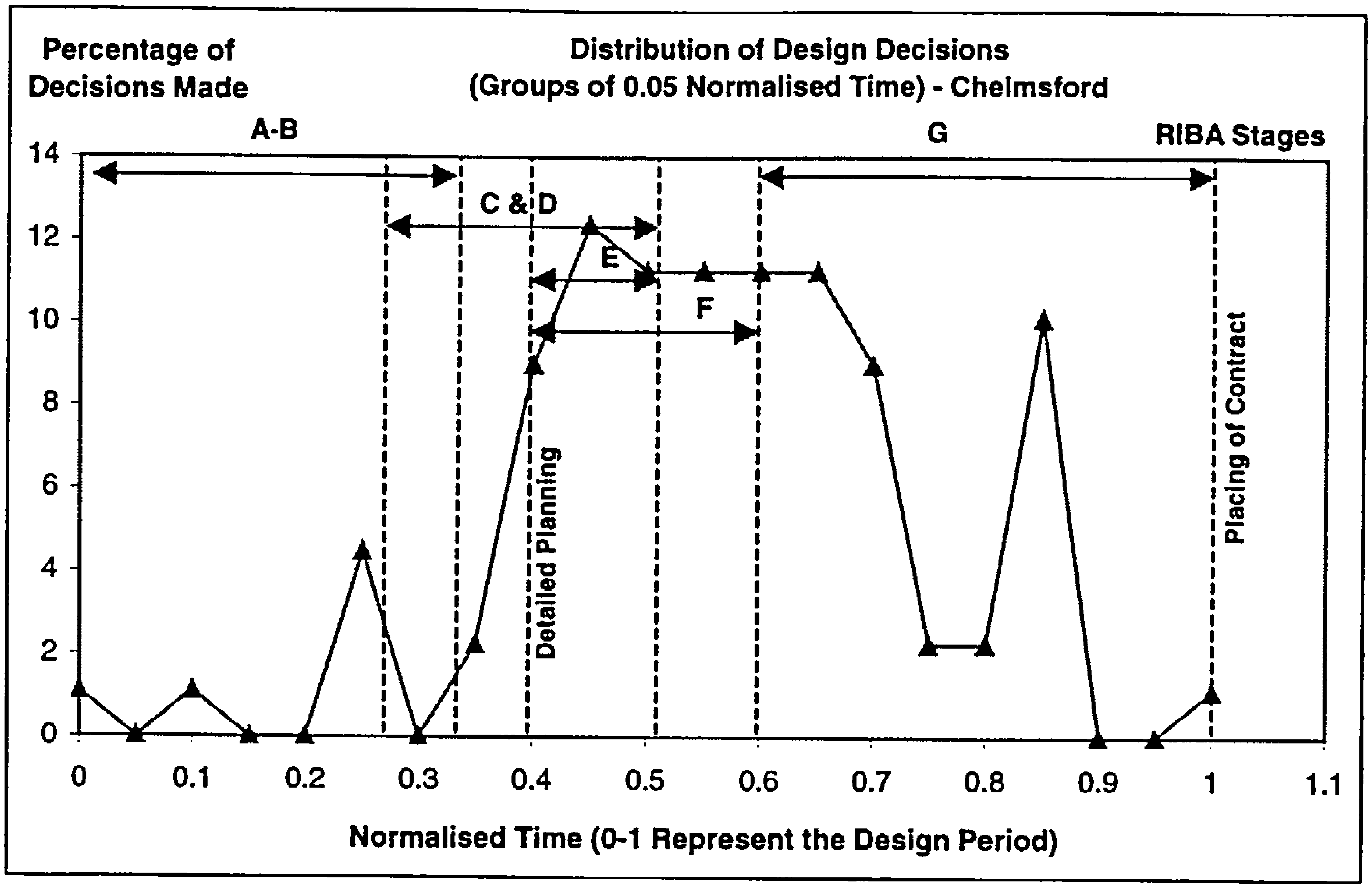


Figure G.3 - Distribution of Design Decisions (Groups of 0.05 Normalised Time) - Chelmsford

Chelmsford Design Team Discipline	Company
Architect	Stanley Bragg Partnership Limited
Architect (A)	Stanley Bragg Partnership Limited
Architect (B)	Stanley Bragg Partnership Limited
Client (Developer)	Shearer Property Group
Client (Developer – B)	Shearer Property Group
Contractor	Hutton Construction
Funders	Morgan Grenfell Asset Management Ltd
Letting Agents	Awbery Lapsa
Local Authority - Planning Officer	Chelmsford Borough Council
Local Authority - Case Officer	Chelmsford Borough Council
Party Wall Surveyor	Keith Douglas Partnership
Planning Supervisor	Rowney Sharman
Project Manager	Rowney Sharman
Quantity Surveyor	Murdoch Green
Structural Engineer	Harris & Sutherlannd

Table G.2 – Design Team (Chelmsford)

Discipline	Joined Project Team	
	Date	Normalised Time
Client	23/11/96	0
Architect	23/11/96	0
Structural Engineer	15/9/97	0.334096
Legal Advisor	23/11/96	0
Project Manager	15/9/97	0.334096
Quantity Surveyor	23/11/96	0
Client's Agent	23/11/96	0

Table G.3 – When Each Design Team Member Joined the Project (Chelmsford)

Decision Maker	Decision Number	Decision Order	Chelmsford Design Decision Made	Normalised Time
Architect	**32**	14	Decide how to interface the new build roof with the existing listed building	0.36842105
Architect	**29**	15	**Configuration of roof (roof form)**	**0.37643021**
Architect	**23**	16	Structural bay dimensions	0.38443936
Architect	**27**	17	**Selection of roof structure material**	**0.41418764**
Architect	**49**	18	Finish for ground and first level floors	0.41418764
Architect	**95**	24	Specification of floor levels	0.41647597
Architect	**28**	26	Selection of roof structure material	0.4382151
Architect	**30**	27	Configuration of roof (roof form)	0.4382151
Architect	**77**	29	Position of service bays	0.46910755
Architect	**78**	30	Traffic routes within the site	0.46910755
Architect	**97**	34	Dimension between external skin (vertical cladding) and gridline	0.47482838
Architect	**90**	36	Windows configuration	0.47940503
Architect	**91**	37	Amount of glazing used in the scheme	0.47940503
Architect	**88**	38	Roof drainage system	0.50114416
Architect	**33**	39	The roofing material for the flat roof areas	0.50572082
Architect	**64**	42	Decision to route all the services together	0.5194508
Architect	**50**	45	Finish for second level floor	0.54004577
Architect	**52**	46	Type of partition for dividing wall between unit 1 and unit 2 in the existing building	0.54919908
Architect	**53**	47	Type of partition for means of escape areas for units 1 and 2	0.54919908
Architect	**55**	48	**The material selection for the external skin**	**0.55377574**
Architect	**96**	51	Connection between vertical cladding (external skin) and floor slab	0.58581236
Architect	**75**	52	Decision to have smoke vents in the escape cores	0.58695652
Architect	**74**	54	Type of fire protection for the steel frame	0.58810069
Architect	**82**	55	The construction type of the stairs	0.58924485
Architect	**56**	56	Selection of material for feature masonry on external skin	0.59153318
Architect	**63**	57	**Route of services (source, route and to - internal within building)**	**0.59153318**
Architect	**41**	58	Specification of fire escape doors to the ginnel walk way	0.60640732
Architect	**44**	59	Specification of listed building internal doors	0.60640732
Architect	**45**	60	Specification of access door to listed building from flat roofs of each unit	0.60640732
Architect	**46**	61	Specification of internal means of escape doors (general)	0.60640732
Architect	**94**	63	Floor finish for the listed building areas	0.61327231
Architect	**2**	65	**Paving layout and materials to the ginnel**	**0.63157895**
Architect	**6**	66	**Paving layout and materials to the ginnel (two more options)**	**0.63157895**
Architect	**83**	67	Paving layout and materials to the ginnel	0.63157895
Architect	**21**	69	Bracing to Steel Frame	0.67505721
Architect	**3**	70	Selection of external lighting fitting	0.68764302
Architect	**9**	71	Specification of external lighting to covered front area of ginnel - beneath alley way	0.68764302
Architect	**16**	75	Determine best position for statutory services meter cupboard	0.69565217
Architect	**65**	77	Redesigned the provision of electrical services	0.73684211
Architect	**66**	79	Size and capacity of each service	0.79290618
Architect	**69**	82	The fire escape strategy for the 3rd floor of the listed building	0.81464531
Architect	**70**	83	Fire escape strategy for the second floors (new build and listed)	0.81464531
Architect	**71**	84	Fire escape strategy for the first floor (new build and listed) 17-18 High Street	0.81464531
Architect	**72**	85	Fire escape strategy for the ground floor (new build and listed)	0.81464531
Architect	**73**	86	Fire escape strategy for the first floor (new build and listed) 15-16 High Street	0.81464531

Architect	92	87	Location of internal and external plant areas	0.81578947
Architect - B	67	43	The selection of the insulating material for the external skin	0.52745995
Architect - B	68	44	The selection of the insulating material for the roof	0.52745995
Architect - C	79	1	To incorporate a lift shaft into the scheme	-0.0080092
Architect - C	93	2	Extent of demolition on site	0.08352403
Architect - C	57	32	Articulate the new build elevations with rendered panels inset within brickwork skin	0.47254005
Client (Developer)	31	6	Choice of roofing material	0.24256293
Client (Developer)	36	9	Size and shape of unit 1	0.35469108
Client (Developer)	37	10	**Size and shape of unit 2**	**0.35469108**
Client (Developer)	39	11	Organisational layout of unit 1	0.35583524
Client (Developer)	40	12	Organisational layout of unit 2	0.35583524
Client (Developer)	81	13	Position of the lift shafts	0.36613272
Client (Developer)	61	28	Decision as to the scope of service provision by the land lord	0.4610984
Client (Developer)	76	31	Position of the access point for service vehicles	0.46910755
Client (Developer)	85	35	Parking position / layout	0.4771167
Client (Developer)	84	53	Materials selection for the parking area	0.58695652
Client (Developer)	89	68	Windows materials / system type	0.65217391
Client (Developer)	8	72	Selection of External Light Fittings to the ginnel	0.68764302
Client (Developer)	25	78	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)	0.76315789
Client (Developer) - B	18	3	Footprint/form of scheme	0.20823799
Client (Developer) - B	35	4	Number of units and their size for the phase 1 development (high street)	0.21395881
Client (Developer) - B	54	5	Selection of system for external skin of new build	0.23684211
Client (Developer) - B	34	7	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)	0.32265446
Client (Developer) - B	24	33	Create a clear area beneath the listed building	0.47254005
Client (Developer) - B	59	49	The material selection for the external skin	0.55377574
Client (Developer) - B	42	62	**Public access doors to ginnel**	**0.60640732**
Client (Developer) - B	43	64	Public access doors to ginnel (change from aluminium in tender document to timber)	0.63043478
Client (Developer) - B	62	73	Route of services (source, route and to - internal within building)	0.69107551
Client (Developer) - B	7	74	Amendment of ginnel paving materials	0.69221968
Client (Developer) - B	60	76	Design of external signage	0.701373

Client (Developer) - B	**38**	88	Re-design of the footprint of unit 2	0.82608696
Contractor	**98**	89	Method of installing piles (design rationalisation)	1
Structural Engineer	**22**	8	Configuration / Layout of the structure	0.34553776
Structural Engineer	**19**	19	Decide whether 'Ground Beams' are a requirement and if so type (substructure)	0.41418764
Structural Engineer	**20**	20	Selection of structural frame for new build	0.41418764
Structural Engineer	**47**	21	Selecting overall floor slab configuration	0.41418764
Structural Engineer	**48**	22	Floor slab configuration at ground level	0.41418764
Structural Engineer	**51**	23	Defined the flat roof structure configuration (units 1 and 2) - new build	0.41418764
Structural Engineer	**26**	25	To retain the existing foundations for the listed building	0.43707094
Structural Engineer	**17**	40	Selection of substructure - type of foundation	0.50572082
Structural Engineer	**80**	41	The construction type for the lift shaft	0.51601831
Structural Engineer	**58**	50	Selection of the material for the internal masonry leaf of external skin (i.e. the internal skin)	0.55377574
Structural Engineer	**86**	80	To combine / separate foul and surface water drainage	0.81006865
Structural Engineer	**87**	81	Routes for foul and surface water drainage	0.81350114

Table G.4 – List of System / Sub-System Level Design Decisions for the Chelmsford Case Study by Order of Decision Maker

Decision Number	Chelmsford Decisions That The Architect Was Involved In Making
5	Decide whether to move forward on 15 000sq ft footprint (45 000 sq. ft total) scheme
8	Selection of external light fittings to the ginnel
17	Selection of substructure -type of foundation
18	footprint/form of scheme
19	Decide whether 'Ground Beams' are a requirement and if so type (substructure)
20	Selection of structural frame for new build
21	Bracing to steel Frame
22	Configuration / Layout of the structure
24	Create a clear area beneath the listed building
25	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)
26	To retain the existing foundations for the listed building
27	**Selection of roof structure material**
28	Selection of roof structure material
30	Configuration of roof (roof form)
31	Choice of roofing material
34	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)
35	Number of units and their size for the phase 1 development (high street)
36	Size and shape of unit 1
37	**Size and shape of unit 2**
38	Re-design of the footprint of unit 2
39	Organisational layout of unit 1
40	Organisational layout of unit 2
42	**Public access doors to ginnel**
43	Public access doors to ginnel (change from aluminium in tender document to timber)
47	Selecting overall floor slab configuration
48	Floor slab configuration at ground level
51	Defined the flat roof structure configuration (units 1 and 2) - new build
54	Selection of system for external skin of new build
58	Selection of the material for the internal masonry leaf of external skin (i.e. the internal skin)
59	The material selection for the external skin
60	Design of external signage
61	Decision as to the scope of service provision by the land lord
62	Route of services (source, route and to - internal within building)
63	**Route of services (source, route and to - internal within building)**
76	Position of the access point for service vehicles
80	The construction type for the lift shaft
81	Position of the lift shafts
84	Materials selection for the parking area
85	Parking position / layout
86	To combine / separate foul and surface water drainage
87	Routes for foul and surface water drainage
89	Windows materials / system type
98	Method of installing piles (design rationalisation)

Table G.5 - List of System / Sub-System Level Design Decisions that the Architect was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Client Was Involved In Making
7	Amendment of ginnel paving materials
18	Footprint/form of scheme
22	Configuration / Layout of the structure
23	Structural bay dimensions
30	Configuration of roof (roof form)
32	Decide how to interface the new build roof with the existing listed building
55	**The material selection for the external skin**
56	Selection of material for feature masonry on external skin
57	Articulate the new build elevations with rendered panels inset within brickwork skin
59	The material selection for the external skin
73	Fire escape strategy for the first floor (new build and listed) 15-16 High Street
74	Type of fire protection for the steel frame
77	Position of service bays
78	Traffic routes within the site
82	The construction type of the stairs
83	Paving layout and materials to the ginnel
90	Windows configuration
91	Amount of glazing used in the scheme
92	Location of internal and external plant areas
93	Extent of demolition on site
94	Floor finish for the listed building areas
95	Specification of floor levels

Table G.6 - List of System / Sub-System Level Design Decisions that the Client was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Client's Agent Was Involved In Making
5	Decide whether to move forward on 15 000sq ft footprint (45 000 sq. ft total) scheme
18	Footprint/form of scheme
22	Configuration / Layout of the structure
34	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)
35	Number of units and their size for the phase 1 development (high street)
36	Size and shape of unit 1
37	**Size and shape of unit 2**
39	Organisational layout of unit 1
40	Organisational layout of unit 2
47	Selecting overall floor slab configuration
49	Finish for ground and first level floors
61	Decision as to the scope of service provision by the land lord
76	Position of the access point for service vehicles
77	Position of service bays
78	Traffic routes within the site
81	Position of the lift shafts
85	Parking position / layout
92	Location of internal and external plant areas
93	Extent of demolition on site
94	Floor finish for the listed building areas
95	Specification of floor levels

Table G.7 - List of System / Sub-System Level Design Decisions that the Client's Agent was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The End User Was Involved In Making
25	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)
38	Re-design of the footprint of unit 2
39	Organisational layout of unit 1
40	Organisational layout of unit 2

Table G.8 - List of System / Sub-System Level Design Decisions that the End User was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Legal Consultant Was Involved In Making
35	Number of units and their size for the phase 1 development (high street)
77	Position of service bays
78	Traffic routes within the site

Table G.9 - List of System / Sub-System Level Design Decisions that the Legal Consultant was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Planning Authority Was Involved In Making
32	Decide how to interface the new build roof with the existing listed building
34	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)
35	Number of units and their size for the phase 1 development (high street)
39	Organisational layout of unit 1
40	Organisational layout of unit 2
54	Selection of system for external skin of new build
57	Articulate the new build elevations with rendered panels inset within brickwork skin
76	Position of the access point for service vehicles
83	Paving layout and materials to the ginnel
86	To combine / separate foul and surface water drainage
89	Windows materials / system type
90	Windows configuration
91	Amount of glazing used in the scheme
93	Extent of demolition on site
94	Floor finish for the listed building areas
95	Specification of floor levels

Table G.10 - List of System / Sub-System Level Design Decisions that the Planning Authority was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Planning Supervisor Was Involved In Making
58	Selection of the material for the internal masonry leaf of external skin (i.e. the internal skin)

Table G.11 - List of System / Sub-System Level Design Decisions that the Planning Supervisor was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Project Manager Was Involved In Making
19	Decide whether 'Ground Beams' are a requirement and if so type (substructure)
20	Selection of structural frame for new build
21	Bracing to steel frame
22	Configuration / Layout of the structure
23	Structural bay dimensions
24	Create a clear area beneath the listed building
30	Configuration of roof (roof form)
34	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)
35	Number of units and their size for the phase 1 development (high street)
38	Re-design of the footprint of unit 2
39	Organisational layout of unit 1
40	Organisational layout of unit 2
47	Selecting overall floor slab configuration
48	Floor slab configuration at ground level
49	Finish for ground and first level floors
55	**The material selection for the external skin**
56	Selection of material for feature masonry on external skin
57	Articulate the new build elevations with rendered panels inset within brickwork skin
58	Selection of the material for the internal masonry leaf of external skin (i.e. the internal skin)

60	Design of external signage
61	Decision as to the scope of service provision by the land lord
62	Route of services (source, route and to - internal within building)
76	Position of the access point for service vehicles
80	The construction type for the lift shaft
81	Position of the lift shafts
82	The construction type of the stairs
83	Paving layout and materials to the ginnel
84	Materials selection for the parking area
85	Parking position / layout
88	Roof drainage system
89	Windows materials / system type
91	Amount of glazing used in the scheme
94	Floor finish for the listed building areas
95	Specification of floor levels
98	Method of installing piles (design rationalisation)

Table G.12 - List of System / Sub-System Level Design Decisions that the Project Manager was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Quantity Surveyor Was Involved In Making
17	Selection of substructure - type of foundation
19	Decide whether 'Ground Beams' are a requirement and if so type (substructure)
20	Selection of structural frame for new build
21	Bracing to steel frame
22	Configuration / Layout of the structure
23	Structural bay dimensions
24	Create a clear area beneath the listed building
25	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)
26	To retain the existing foundations for the listed building
28	Selection of roof structure material
30	Configuration of roof (roof form)
32	Decide how to interface the new build roof with the existing listed building
34	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)
35	Number of units and their size for the phase 1 development (high street)
36	Size and shape of unit 1
37	**Size and shape of unit 2**
41	Specification of fire escape doors to the ginnel walk way
42	public access doors to ginnel
43	public access doors to ginnel (change from aluminium in tender document to timber)
47	Selecting overall floor slab configuration
48	Floor slab configuration at ground level
49	Finish for ground and first level floors
50	Finish for second level floor
51	Defined the flat roof structure configuration (units 1 and 2) - new build
55	**The material selection for the external skin**
56	Selection of material for feature masonry on external skin
58	Selection of the material for the internal masonry leaf of external skin (i.e. the internal skin)
74	Type of fire protection for the steel frame
76	Position of the access point for service vehicles

77	Position of service bays
78	Traffic routes within the site
80	The construction type for the lift shaft
81	Position of the lift shafts
82	The construction type of the stairs
83	Paving layout and materials to the ginnel
84	Materials selection for the parking area
86	To combine / separate foul and surface water drainage
87	Routes for foul and surface water drainage
88	Roof drainage system
89	Windows materials / system type
91	Amount of glazing used in the scheme
93	Extent of demolition on site
94	Floor finish for the listed building areas
95	Specification of floor levels
96	Connection between vertical cladding (external skin) and floor slab
97	Dimension between external skin (vertical cladding) and gridline
98	Method of installing piles (design rationalisation)

Table G.13 - List of System / Sub-System Level Design Decisions that the Quantity Surveyor was Involved in Making (Chelmsford)

Decision Number	Chelmsford Decisions That The Specialist Consultants Was Involved In Making	Specify Specialist Consultant
66	Chelmsford size and capacity of each service	Statutory authorities
69	The fire escape strategy for the 3rd floor of the listed building	Building control officer - statutory authorities
70	Fire escape strategy for the second floors (new build and listed)	Building control officer - statutory authorities
71	Fire escape strategy for the first floor (new build and listed) 17-18 High Street	Building control officer - statutory authorities
72	Fire escape strategy for the ground floor (new build and listed)	Building control officer - statutory authorities
73	Fire escape strategy for the first floor (new build and listed) 15-16 High Street	Building control officer - statutory authorities,
86	To combine / separate foul and surface water drainage	Statutory authority (Anglian water)
87	Routes for foul and surface water drainage	Drainage company: Anglian Water
98	Method of installing piles (design rationalisation)	Piling subcontractor

Table G.14 - List of System / Sub-System Level Design Decisions that Specialist Consultants were Involved in Making (Chelmsford)

Decision Number	Decisions That The Structural Engineer Was Involved In Making
17	Selection of substructure - type of foundation
19	Decide whether 'Ground Beams' are a requirement and if so type (substructure)
20	Selection of structural frame for new build
21	Bracing to steel frame
23	Structural bay dimensions
24	Create a clear area beneath the listed building
25	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)
28	Selection of roof structure material
30	Configuration of roof (roof form)
36	Size and shape of unit 1
37	**Size and shape of unit 2**
39	Organisational layout of unit 1
40	Organisational layout of unit 2
49	Finish for ground and first level floors
50	Finish for second level floor
74	Type of fire protection for the steel frame
76	Position of the access point for service vehicles
77	Position of service bays
78	Traffic routes within the site
81	Position of the lift shafts
82	The construction type of the stairs
84	Materials selection for the parking area
88	Roof drainage system
91	Amount of glazing used in the scheme
92	Location of internal and external plant areas
94	Floor finish for the listed building areas
95	Specification of floor levels
96	Connection between vertical cladding (external skin) and floor slab
97	Dimension between external skin (vertical cladding) and gridline
98	Method of installing piles (design rationalisation)

Table G.15 - List of System / Sub-System Level Design Decisions that the Structural Engineer was Involved in Making (Chelmsford)

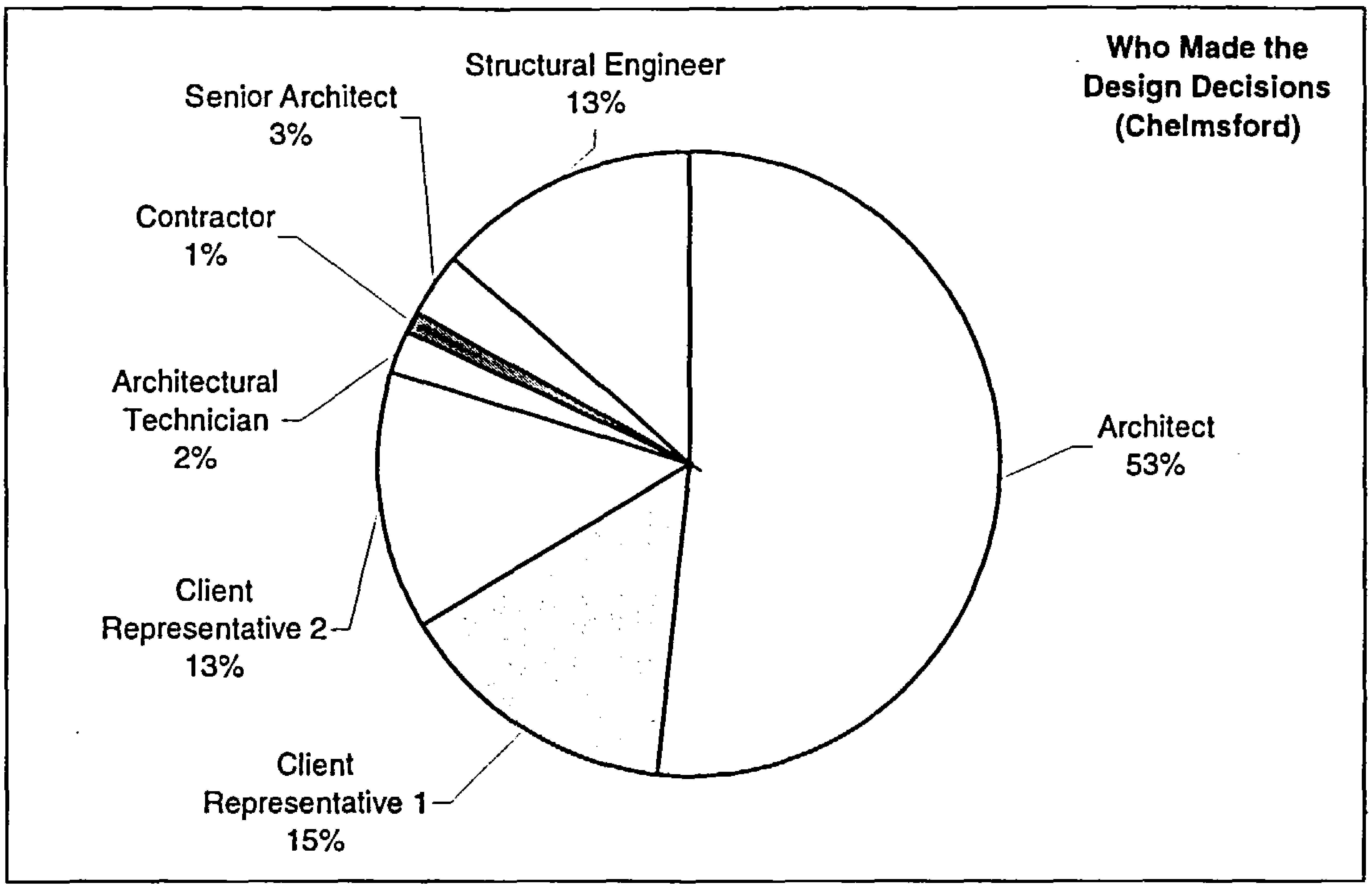


Figure G.4 – Who Made the Design Decisions (Chelmsford)

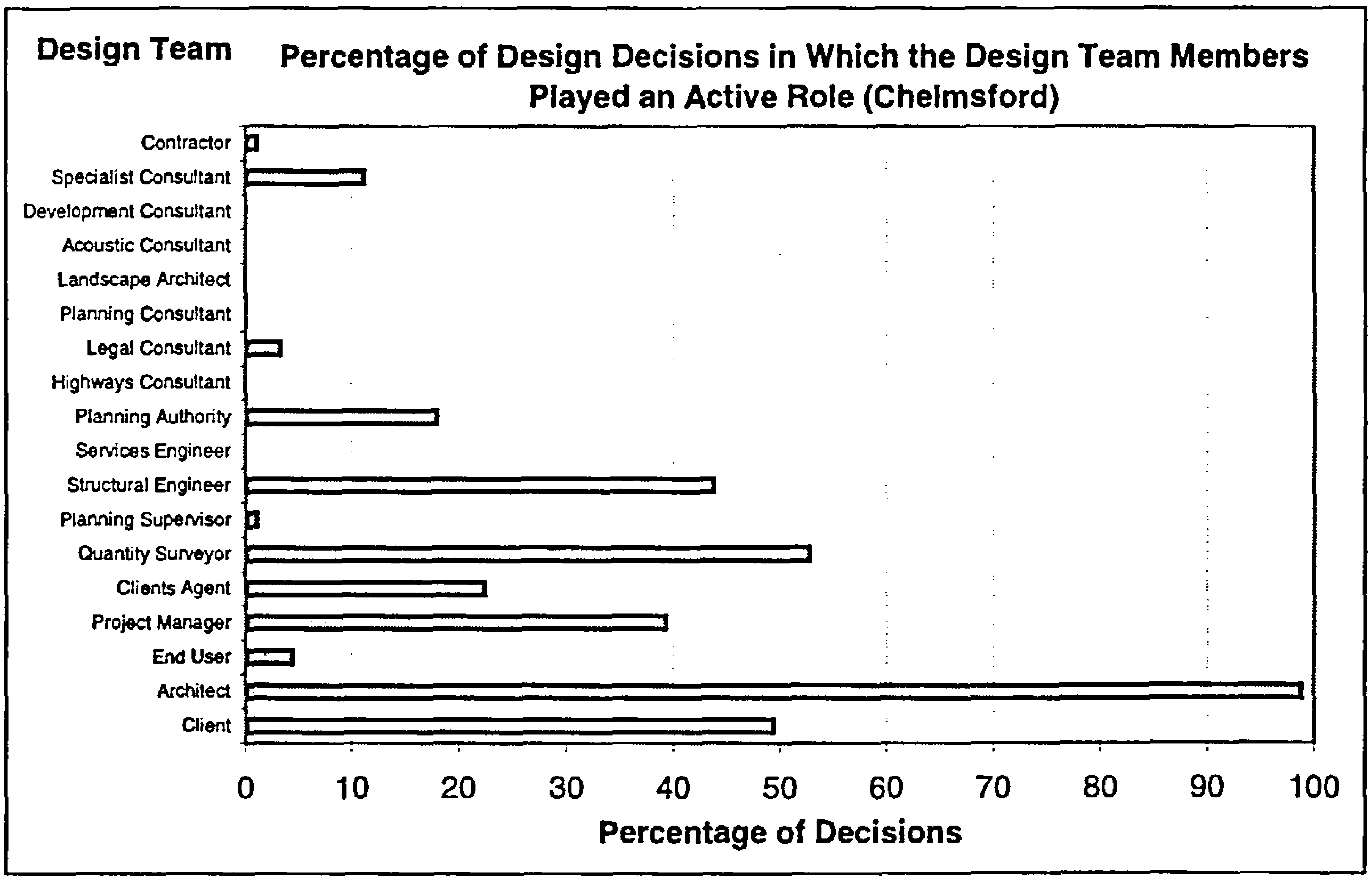


Figure G.5 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Chelmsford)

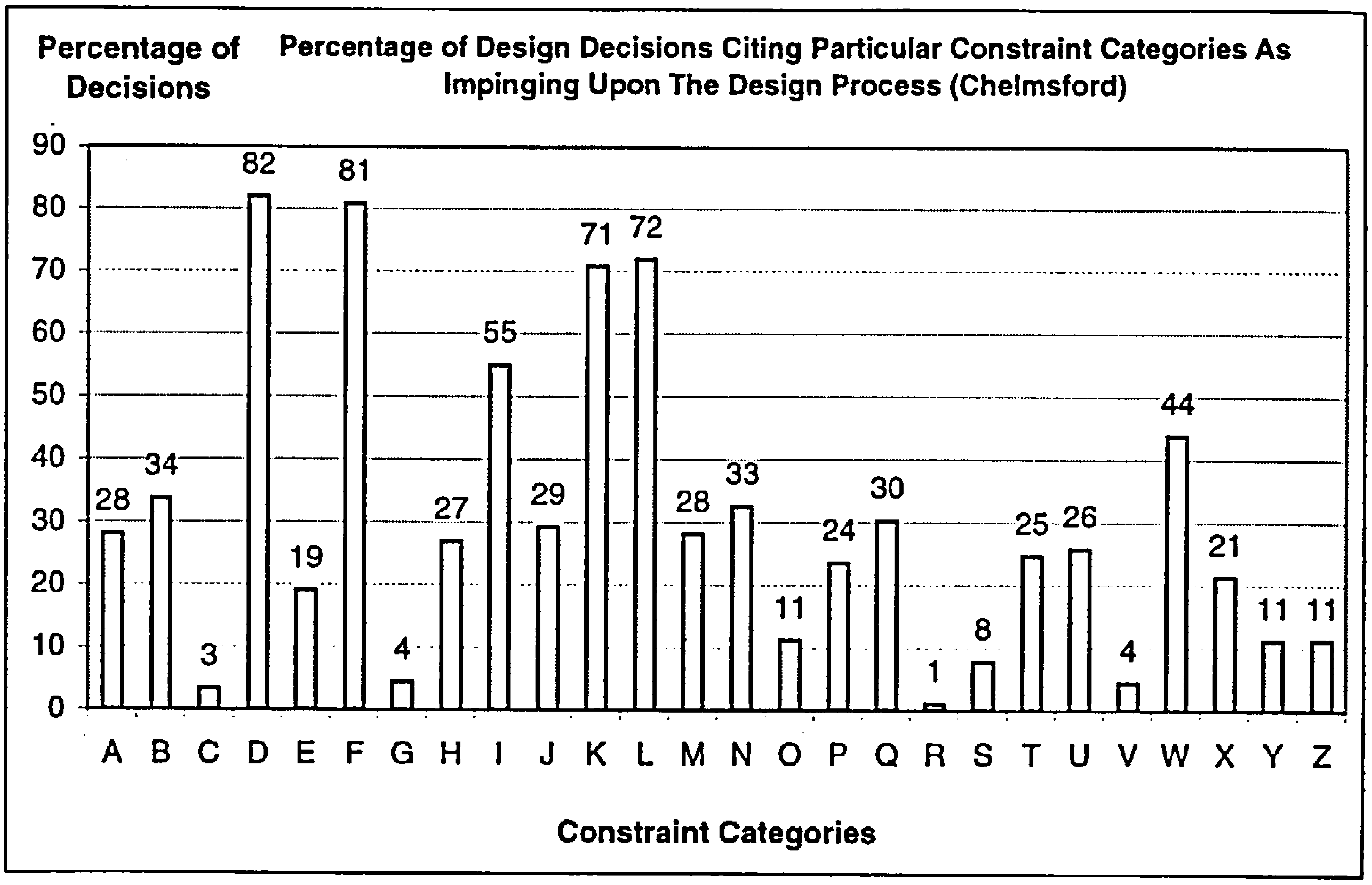


Figure G.6 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Chelmsford)

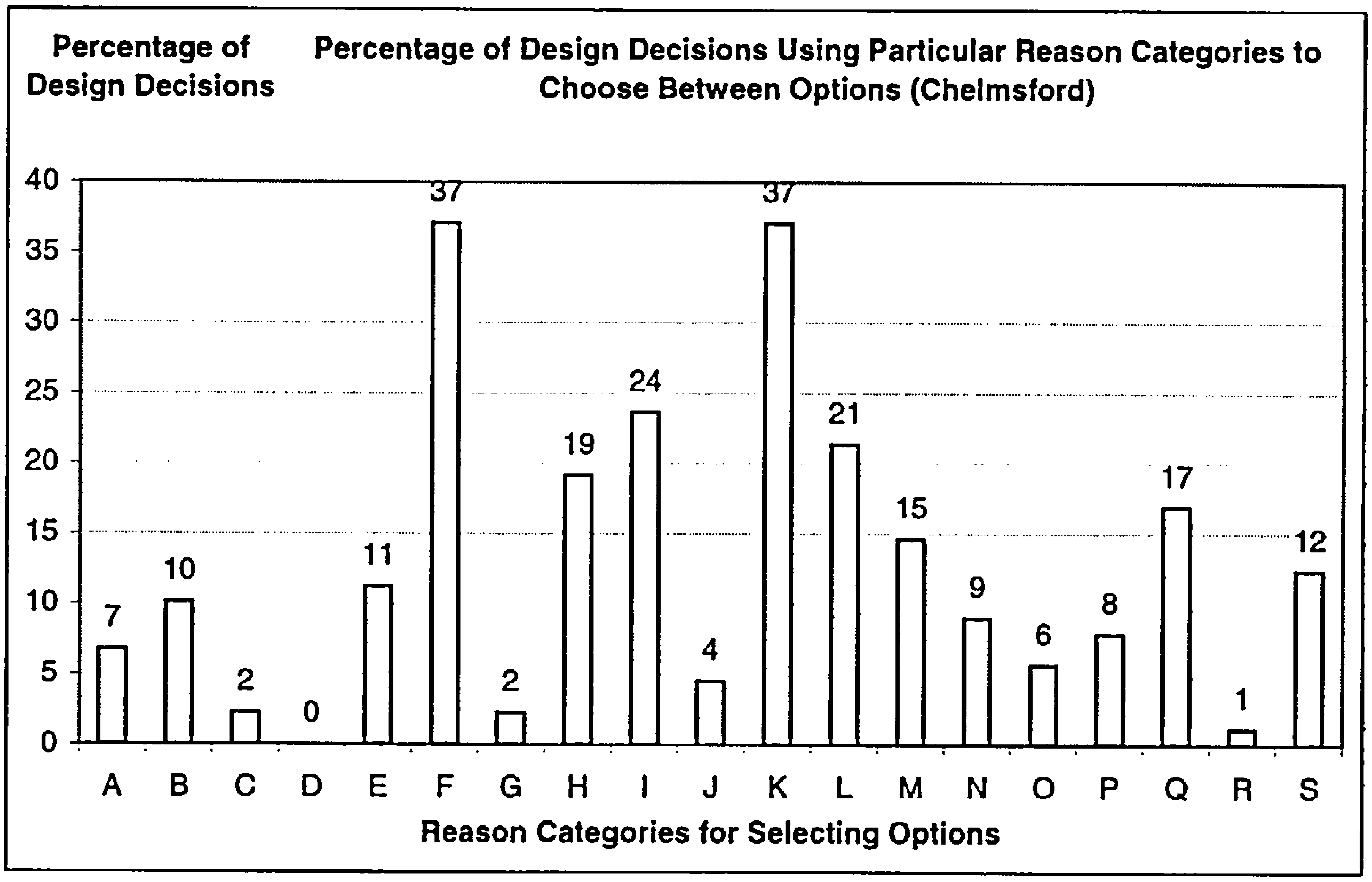


Figure G.7 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Chelmsford)

Decision Number	Chelmsford Decision Made	Constraints Impinging Design - Categories Cited	Reason For Selecting Options - Categories Cited
2	**Paving layout and materials to the ginnel**	**I,L,M**	**F,I,Q**
3	Selection of external lighting fitting	I,L,M	F,M
6	**Paving layout and materials to the ginnel (two more options)**	**I,L,U**	**F,Q**
7	Amendment of ginnel paving materials	I,L	L,M
8	Selection of external light fittings to the ginnel	D,F,H,I,K,L,U,Z	F
9	Specification of external lighting to covered front area of ginnel - beneath alley way	D,F,H,I,K,L,M,Q,U,Z	F
16	Determine best position for statutory services meter cupboard	B,L	F
17	Selection of substructure - type of foundation	D,F,I,N,X	F,G,H,R,S
18	Footprint/form of scheme		F,G,S
19	Decide whether 'ground beams' are a requirement and if so type (substructure)	B,D,F,L,M,Q,T,U,X	E
20	Selection of structural frame for new build	D,E,F,H,I,K,L,O,N	B,I,K,O
21	Bracing to steel frame	F,I,K,L,M	F,K,L
22	Configuration / layout of the structure	B,D,E,F,H,I,J,K,Q	I,J,K,M
23	Structural bay dimensions	B,D,E,F,I,Q,U	I,K
24	Create a clear area beneath the listed building	D,E,F,H,I,L,N	K,Q
25	Remove excess structure at the interface of new and retained buildings (note that the two are to be kept separate)	B,D,F,I,K,M,Q	F,K,M
26	To retain the existing foundations for the listed building	D,F,H,I,K,O,X	A,I,O
27	**Selection of roof structure material**	**A,D,F,H,I,J,K,L**	**H,I**
28	Selection of roof structure material	A,D,F,H,I,J,K,L	F,H,K
29	**Configuration of roof (roof form)**	**A,D,F,H,I,J,L,U**	**L,Q**
30	Configuration of roof (roof form)	A,D,F,H,I,J,L,M,U	K
31	Choice of roofing material	D,F,H,I,J,K,L,M,P,Q,W	L,M,Q
32	Decide how to interface the new build roof with the existing listed building	B,D,F,H,I,J,K,L,Q,U,W	F,H,I,L,Q
33	The roofing material for the flat roof areas	D,F,H,I,J,K,N,P,W,X	H,I,N,P
34	To phase the development of the Chelmsford site (the site comprised the high street and riverside developments)	D,I,J,L,O,S,U,X	E,F,S
35	Number of units and their size for the phase 1 development (high street)	B,C,D,E,I,L,T,U,X	F,K,S
36	Size and shape of unit 1	B,D,E,F,I,K,L,T,U,W	H,I,K
37	**Size and shape of unit 2**	**B,D,E,F,I,K,L,T,U,W**	**H,I,K**
38	Re-design of the footprint of unit 2	B,D,E,F,I,K,L,T,U,W	F,S
39	Organisational layout of unit 1	A,B,D,F,K,L,U	E
40	Organisational layout of unit 2	A,B,D,F,K,L,	M

		U	
41	Specification of fire escape doors to the ginnel walk way	F,I,J,L,P,W,Z	B,E
42	**Public access doors to ginnel**	**F,J,K,L,P,Q,V,W,Z**	**I,M,P**
43	Public access doors to ginnel (change from aluminium in tender document to timber)	F,J,K,L,P,Q,V,W,Z	L,P,Q
44	Specification of listed building internal doors	F,L,N,T,W	Q
45	Specification of access door to listed building from flat roofs of each unit	F,J,K,N,P,Q,W,Z	F
46	Specification of internal means of escape doors (general)	K,N	A,J,L
47	Selecting overall floor slab configuration	B,D,F,H,I,K,N,O,U,X	B,K,M
48	Floor slab configuration at ground level	A,D,F,H,I,K,N,O,X	B,F,H,K,N,O
49	Finish for ground and first level floors	A,D,F,H,I,J,K,O,P,V	A,J
50	Finish for second level floor	A,D,F,H,I,J,K,O,P,V	K
51	Defined the flat roof structure configuration (units 1 and 2) - new build	D,F,K,N,P	E,F,H
52	Type of partition for dividing wall between unit 1 and unit 2 in the existing building	B,D,F,K,L,N,Q,W	H,I,N
53	Type of partition for means of escape areas for units 1 and 2	D,F,K,L,N,Q,W	F,I,K,N
54	Selection of system for external skin of new build	D,F,L,M,N,P,Q,T,W	E,L,M
55	**The material selection for the external skin**	**D,F,I,K,L,Q,W**	**F,Q**
56	Selection of material for feature masonry on external skin	D,F,I,K,L,M,Q,W	F,Q
57	Articulate the new build elevations with rendered panels inset within brickwork skin	D,F,L,P,Q,Z	I,L,Q
58	Selection of the material for the internal masonry leaf of external skin (i.e. the internal skin)	A,D,F,K,L,N,W	A,F,H,J,K
59	The material selection for the external skin	D,F,I,K,L,Q,W	M
60	Design of external signage	A,D,F,I,J,L,M,P,Q,W	I
61	Decision as to the scope of service provision by the land lord	A,B,D,I,K,L,M,W	I,K,P
62	Route of services (source, route and to - internal within building)	A,B,D,G,M,P,T,U,X,Y	B,H,M,P
63	**Route of services (source, route and to - internal within building)**	**A,B,D,G,M,T,X,Y**	**H,K,P**
64	Decision to route all the services together	B,D,G,I,J,K,M,P	A,K
65	Redesigned the provision of electrical services	A,B,D,F,I,M,T	E,F,S
66	Size and capacity of each service	A,B,F,K,L,U,Y	B,C,L
67	The selection of the insulating material for the external skin	A,B,D,F,K,L,M,U,W,Y	B,K
68	The selection of the insulating material for the roof	A,B,D,F,K,L,M,U,W,Y	B,K
69	The fire escape strategy or the 3rd floor of the listed building	D,F,K,L,N,S,T,W	L
70	Fire escape strategy for the second floors (new build and listed)	D,F,K,L,N,S,T,W	I,K
71	Fire escape strategy for the first floor (new build and listed) 17-18 high street	D,F,K,L,N,S,	L

		T,W	
72	Fire escape strategy for the ground floor (new build and listed)	D,F,K,L,N,S, T,W	F,I,L,N
73	Fire escape strategy for the first floor (new build and listed) 15-16 high street	D,F,K,L,N,S, T,W	F,I,K,L
74	Type of fire protection for the steel frame	D,F,H,K,L,N, O,P,Q,U	H,K,OP
75	Decision to have smoke vents in the escape cores	L,N,S	C,L,N
76	Position of the access point for service vehicles	D,F,J,K,L,T, X	F,K,S
77	Position of service bays	A,D,E,F,J,T, X	F,K,S
78	Traffic routes within the site	A,C,D,E,F,J, T,X	F,K,S
79	To incorporate a lift shaft into the scheme	D,E,I,K,L	K
80	The construction type for the lift shaft	A,B,D,F,H,J, K,N,Q,Y	F,H
81	Position of the lift shafts	A,B,D,E,F,I, K,M,Q,U,X	I
82	The construction type of the stairs	A,B,D,F,H,K, L,M,N,O,Q,Y	B,F,K,H,O
83	Paving layout and materials to the ginnel	D,F,I,K,L,M, P,Q,W,X	I,L,M,Q
84	Materials selection for the parking area	B,D,F,I,J,K,L ,M,W,X,Y	K,M,N
85	Parking position / layout	C,D,F,L,T,X	F,K,S
86	To combine / separate foul and surface water drainage	B,D,F,K,L,M	L
87	Routes for foul and surface water drainage	D,E,F,G,J,K, L,P,X	E
88	Roof drainage system	D,E,F,I,P,T, W	A,E
89	Windows materials / system type	I,J,K,L,M,N, P,W,Z	K,L
90	Windows configuration	D,F,I,K,Q,W, Z	F,H,K,N,Q
91	Amount of glazing used in the scheme	D,F,I,K,N,Q, W,Z	Q
92	Location of internal and external plant areas	A,B,D,E,F,I, K,L,M,N,P,Q ,W,Y	E
93	Extent of demolition on site	D,E,F,H,J,K, L,R,T,W	F,L,Q,S
94	Floor finish for the listed building areas	A,B,D,F,H,I, J,K,L,P,Q,T, W,Y	F,I,L
95	Specification of floor levels	B,D,F,H,I,K, L,N,Q,X	F,K,M
96	Connection between vertical cladding (external skin) and floor slab	D,F,K,L,N,W	K
97	Dimension between external skin (vertical cladding) and gridline	D,E,F,K,L,N, W	H,K
98	Method of installing piles (design rationalisation)	D,F,K,L,O,U, W	I,O

Table G.16 - List of System / Sub-System Level Design Decisions with Corresponding 'Constraint' and 'Reasons For Selection' Categories Cited (Chelmsford)

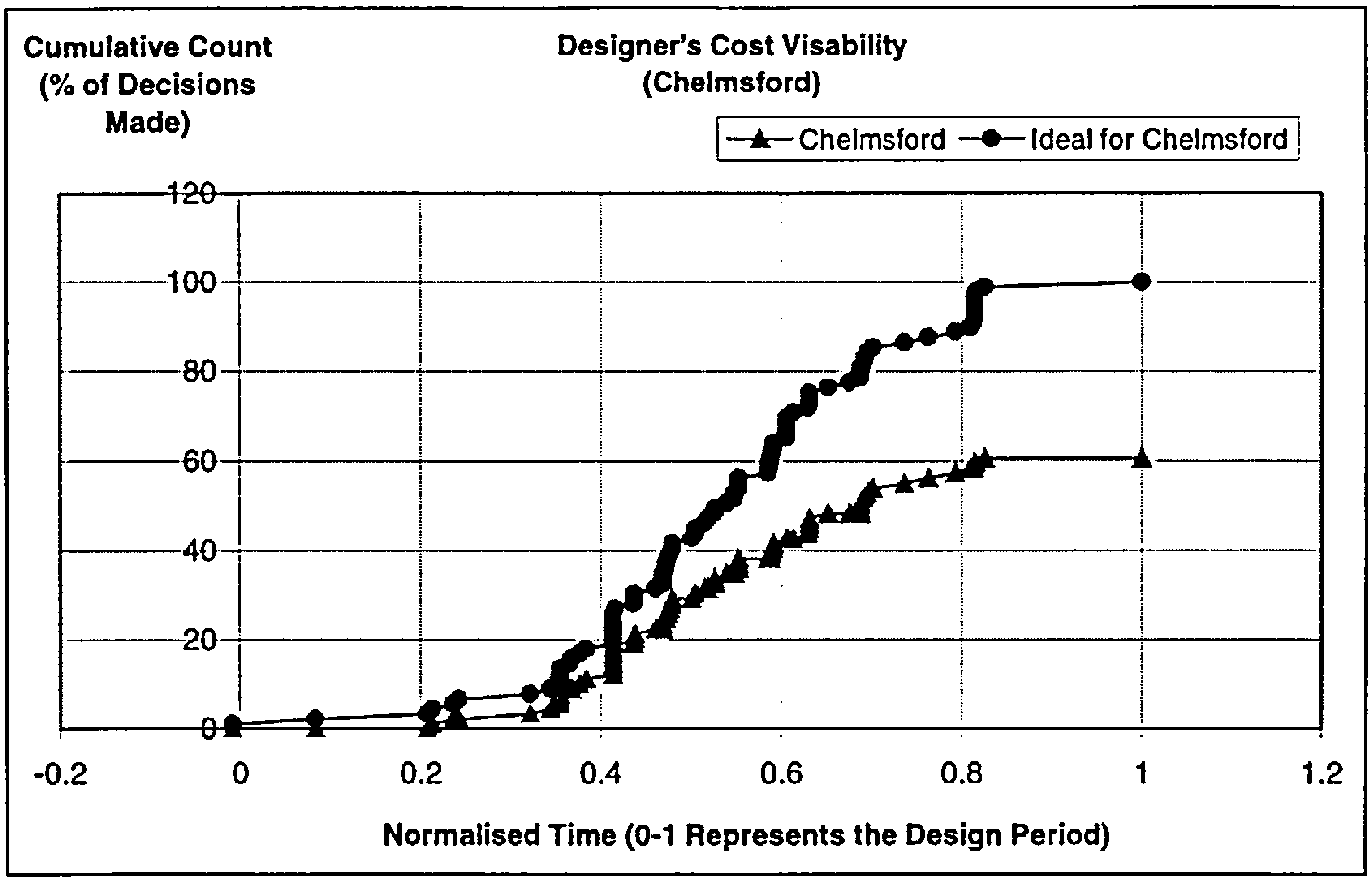


Figure G.8 – Designer's Cost Visibility (Chelmsford)

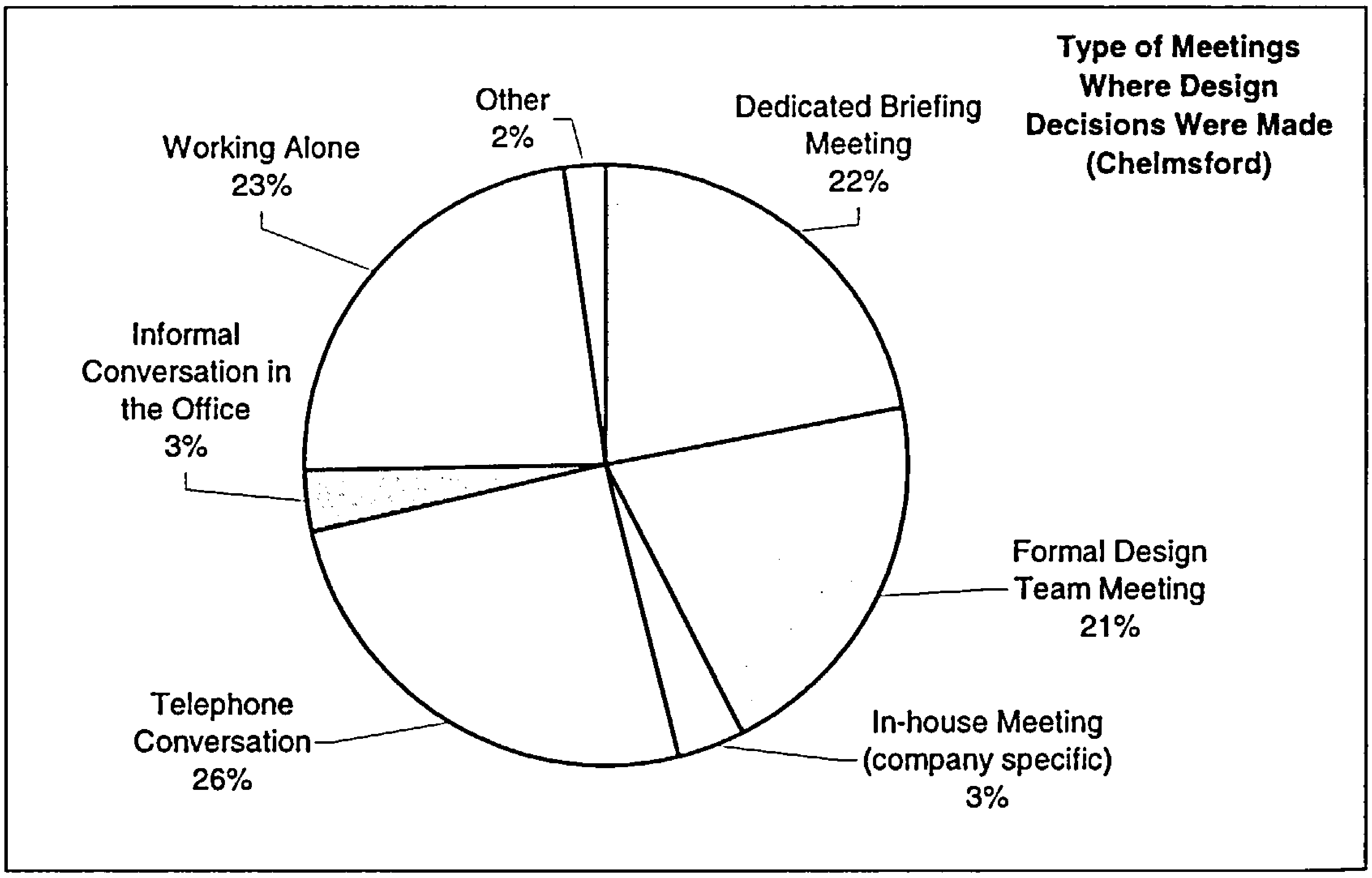


Figure G.9 – The Types of Meetings Where Design Decisions Were Made (Chelmsford)

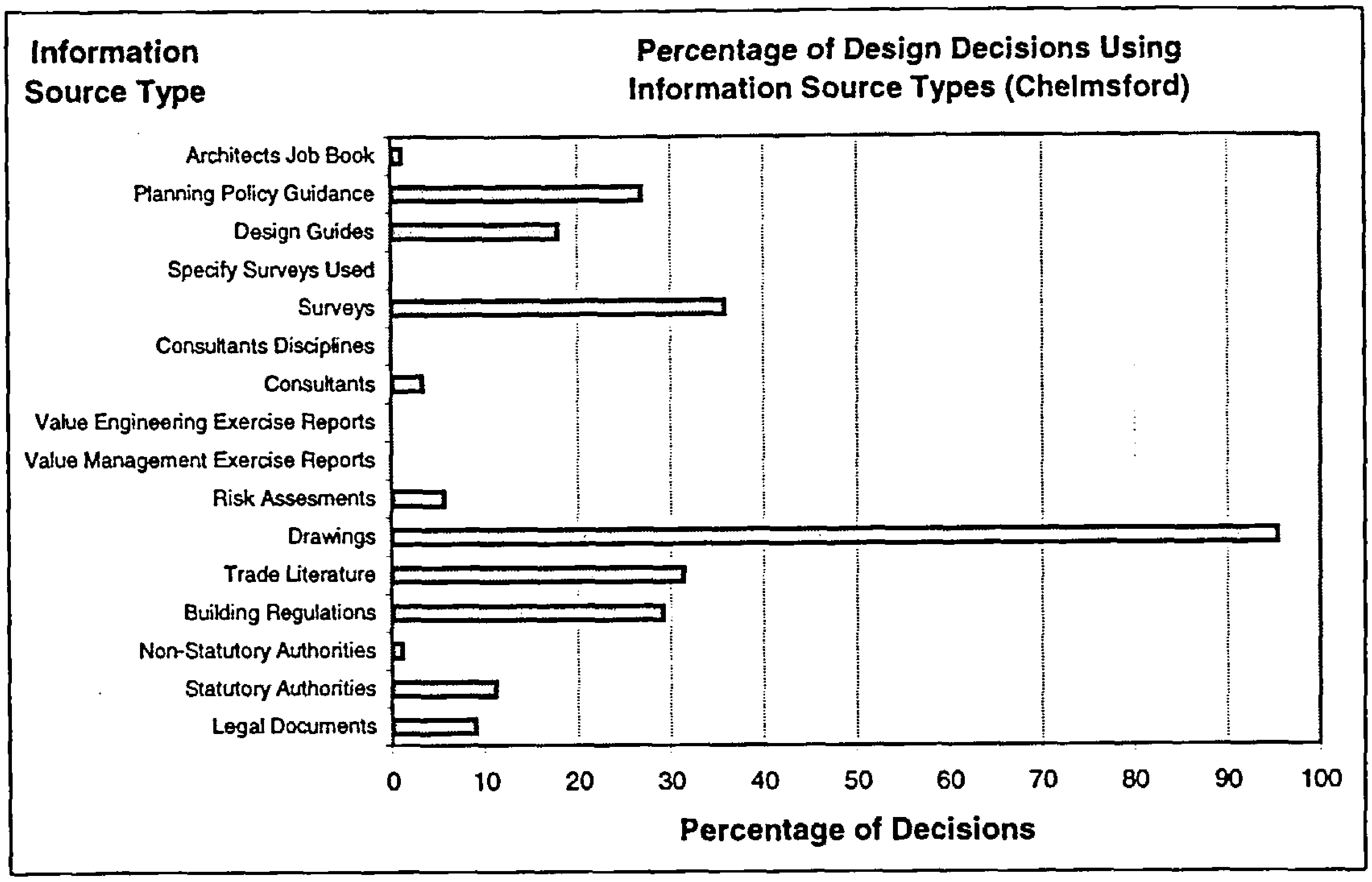


Figure G.10 – Percentage of Design Decisions Using Particular Information Source Types (Chelmsford)

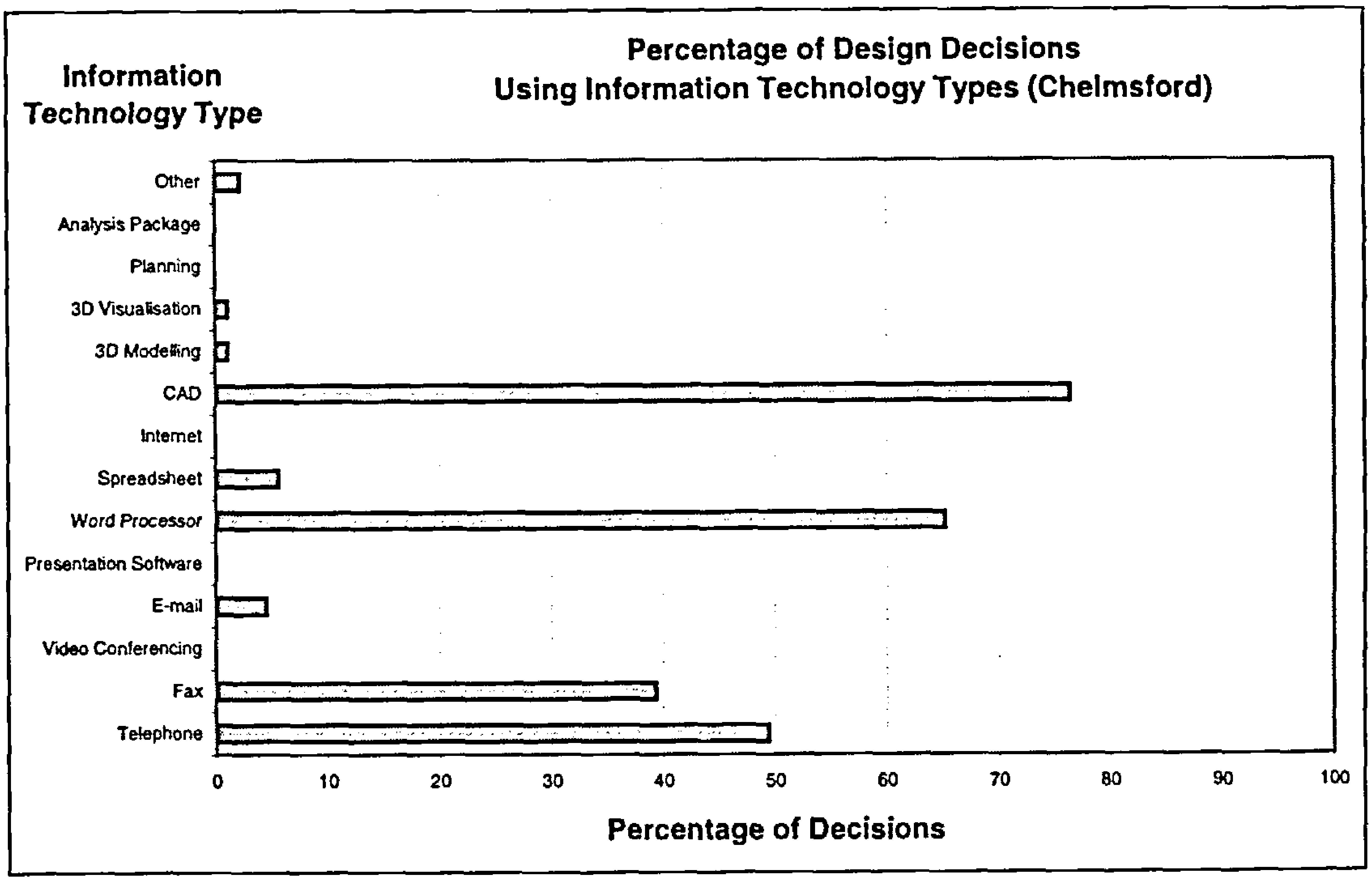


Figure G.11 – Percentage of Design Decisions Using Particular Information Technology Types (Chelmsford)

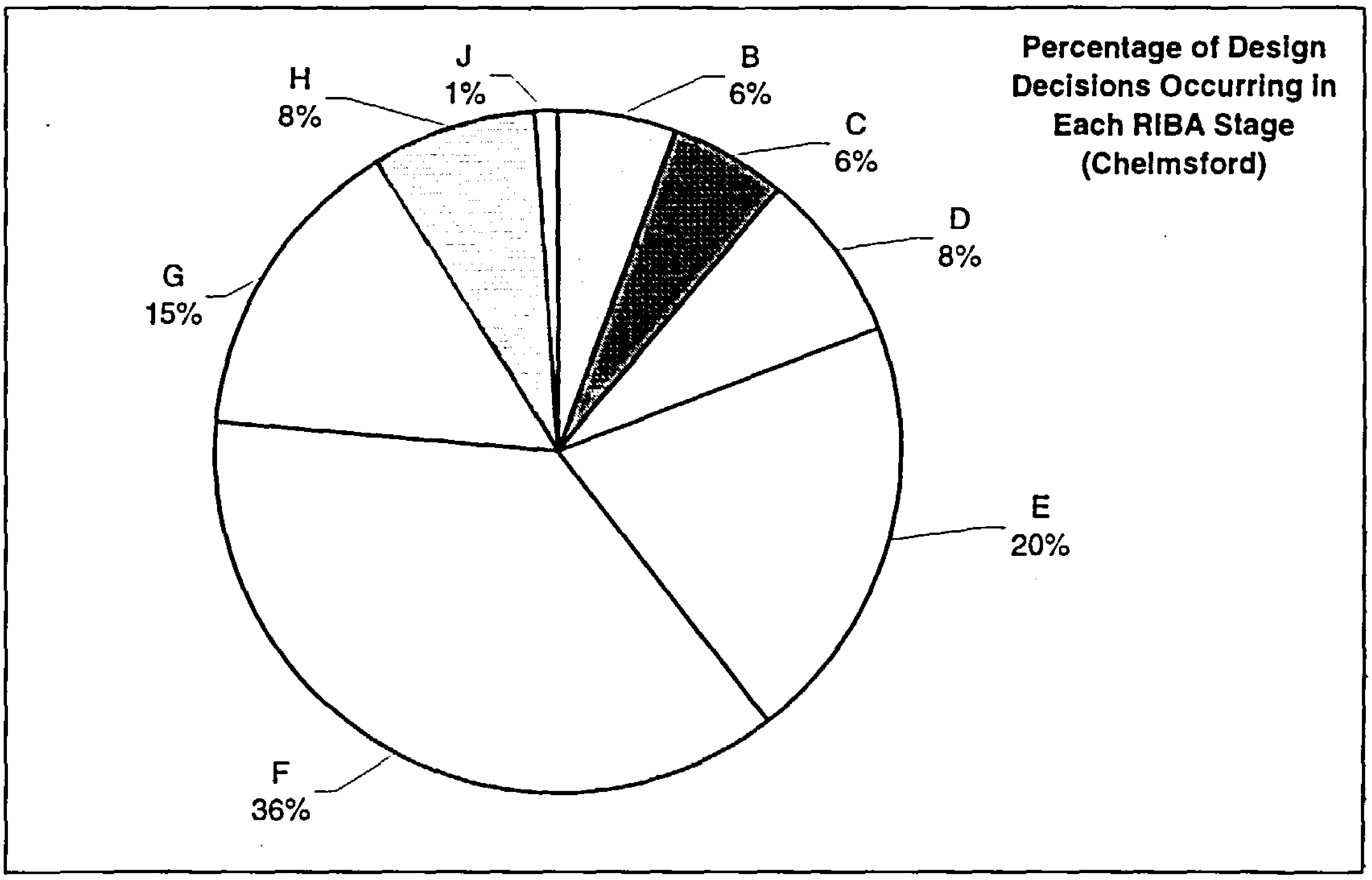


Figure G.12 – Percentage of Design Decisions Occurring in Each RIBA Stage (Chelmsford)

APPENDIX H

List of Figures

Figure H.1 - Cumulative Count of Design Decisions Made Against Normalised Time (Gatwick) ... 7

Figure H.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) - Gatwick 7

Figure H.3 - Distribution of Design Decisions (Groups of 0.05 Normalised Time) – Gatwick 8

Figure H.4 – Who Made the Design Decisions (Gatwick) 22

Figure H.5 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Gatwick) 22

Figure H.6 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Gatwick) 23

Figure H.7 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Gatwick) 23

Figure H.8 – Designer's Cost Visibility (Gatwick) 27

Figure H.9 – The Types of Meetings Where Design Decisions Were Made (Gatwick) 27

Figure H.10 – Percentage of Design Decisions Using Particular Information Source Types (Gatwick) 28

Figure H.11 – Percentage of Design Decisions Using Particular Information Technology Types (Gatwick) 28

Figure H.12 – Percentage of Design Decisions Occurring in Each BAA Stage (Gatwick) 29

List of Tables

Table H.1 – List of System / Sub-System Level Design Decisions for the Gatwick Case Study by Order of Decision Occurrence 6

Table H.2 – Design Team (Gatwick) 9

Table H.3 – List of System / Sub-System Level Design Decisions for the Gatwick Case Study by Order of Decision Maker 13

Table H.4 - List of System / Sub-System Level Design Decisions that the Architect was Involved in Making (Gatwick) 15

Table H.5 - List of System / Sub-System Level Design Decisions that the Client's Agent was Involved in Making (Gatwick) 15

Table H.6 - List of System / Sub-System Level Design Decisions that the End User was Involved in Making (Gatwick) 16

Table H.7 - List of System / Sub-System Level Design Decisions that the Highways Engineer was Involved in Making (Gatwick) 16

Table H.8 - List of System / Sub-System Level Design Decisions that the Planning Supervisor was Involved in Making (Gatwick) 16

Table H.9 - List of System / Sub-System Level Design Decisions that the Project Manager was Involved in Making (Gatwick) 17

Table H.11 - List of System / Sub-System Level Design Decisions that the Services Engineer was Involved in Making (Gatwick) 19

Table H.12 - List of System / Sub-System Level Design Decisions that Specialist Consultants were Involved in Making (Gatwick) 20

Table H.13 - List of System / Sub-System Level Design Decisions that the Structural Engineer was involved in Making (Gatwick) 21

Table H.14 - List of System / Sub-System Level Design Decisions with Corresponding 'Constraint' and 'Reasons For Selection' Categories Cited (Gatwick) 26

Decision Maker	Decision Number	Decision Order	Gatwick Design Decision Made	Normalised Time
Client - BAA	**87**	1	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2	-0.0177665
Services Engineer	**77**	2	Scope of service provision for retail / catering units	0.005076142
Structural Engineer	**69**	3	Type of material for frame	0.083756345
QS	**53**	4	Basic floor plate and space usage	0.172588832
Architect - GRAs	**1**	5	Floor finish zone - none structural element	0.230964467
BAA Project Manager	**4**	6	Building structure	0.230964467
BAA Project Board	**3**	7	Building height	0.230964467
Structural Engineer	**2**	8	Floor finish materials	0.230964467
Structural Engineer	**5**	9	Floor slab thickness set at 150mm	0.266497462
Services Engineer	**54**	10	Type of material for the external face of the cladding for the entire extension	0.312182741
Architect - Fitch	**82**	11	To use mechanically assisted ventilation and cooling	0.314720812
BAA Project Manager	**6**	12	Plant locations	0.317258883
BAA Project Manager	**7**	13	Main extension roof profile	0.317258883
Services Engineer	**50**	14	Selecting the grid dimensions	0.317258883
Architect - GRAs	**10**	15	Pier 2/3 access ramp & transfers configuration	0.352791878
Architect - Fitch	**9**	16	Location of Commercially Important Persons (CIP) location	0.352791878
Services Engineer	**8**	17	**Service riser location**	**0.352791878**
BAA Project Manager	**12**	18	Location of new WC facilities	0.370558376
Structural Engineer	**11**	19	Cladding module size	0.370558376
Client - BAA	**15**	20	Escape routes	0.388324873
BAA Project Manager	**14**	21	SW corner building perimeter - Build in existing space	0.388324873
Architect - Fitch	**16**	22	Floor Levels for level 3 & level 4	0.388324873
Services Engineer	**51**	23	To have a 24m span over the air side road - the road goes underneath the extension on the South West corner	0.393401015
Services Engineer	**52**	24	Locations of the structural columns with respect to the existing passenger link bridges taking departing and arriving passengers from the pier to the terminal	0.393401015
Architect - GRAs	**18**	25	Wing Tip Clearances to the end of building - is SW corner too close to wing tip of aircraft	0.406091371
Architect - Fitch	**39**	26	Decided general location of sub station (not specific place) just the level	0.406091371

Architect - Fitch	40	27	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)	0.406091371
Services Engineer	17	28	Service riser location (See number 8 same details)	0.406091371
Services Engineer	19	29	Level 5 WC location (See no. 12)	0.406091371
Services Engineer	23	30	**Fix specialist systems strategy including fire alarms, CCTV, door access, FIS public address**	**0.406091371**
Services Engineer	38	31	How to supply the electrical power supply of the building (2.4MVA) - covers all uses within the extension	0.406091371
Architect - GRAs	20	32	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction	0.434010152
BAA Project Manager	21	33	Level 5 finish floor level	0.434010152
Architect - Fitch	78	34	Incoming service provision (routing of) electricity, water, drainage	0.439086294
QS	24	35	Power strategy (me2) LV distribution	0.444162437
Services Engineer	22	36	Mechanical Strategy (ME1 on Project Process)	0.444162437
Architect - GRAs	35	37	Fire compartmentation for whole of project fixity SC4	0.469543147
BAA Project Manager	25	38	Smoke Strategy (ME3) for levels 3 and 4/5	0.469543147
BAA Project Manager	34	39	Roof level	0.469543147
Services Engineer	26	40	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas	0.469543147
Services Engineer	27	41	Public Health primary services routes	0.469543147
Client - BAA	28	42	Retail space layout	0.472081218
Client - BAA	31	43	**Number and location of Seating Areas**	**0.472081218**
BAA Project Manager	29	44	Retail storage area locations and access	0.472081218
BAA Project Manager	30	45	Location of CIP Lounges and associated access routes	0.472081218
BAA Project Board	33	46	**Main airside road realignment**	**0.47715736**
Structural Engineer	32	47	Type of roof liner & support	0.47715736
Architect - Fitch	85	48	Decision to have a goods lift located adjacent to the west stair	0.489847716
Services Engineer	70	49	The type of foundation to be used for the extension	0.5
Client - BAA	62	50	Passenger segregation within the area affected by departures lounge project	0.510152284
QS	61	51	Concept stage wayfinding system	0.510152284
Structural Engineer	36	52	Were is the front edge of the building	0.543147208
Client - BAA	73	53	Whether to screed (floor finish issue) tenanted areas or not	0.560913706
BAA Project Board	42	54	Allow the BAA project process to be changed to allow works to commence before the required level of cost certainty achieved.	0.560913706
Framework Contractor	41	55	Dimension between gridline and cladding.	0.598984772

Architect - Fitch	**86**	56	Routes for foul and surface water drainage	0.609137056
Architect - Fitch	**65**	57	To use an alternative supplier for the bonded store hoist (lift for bonded store - store for duty free area)	0.626903553
BAA Project Board	**48**	58	This is the detail of the connection between vertical cladding and the floor slab at columns - interface issue between two packages using different contractors - see fixity no. 37 for general statement	0.629441624
Client - BAA	**83**	59	Specific requirements for CCTV	0.649746193
Client - BAA	**84**	60	Specific requirements for swipe card entry points	0.649746193
Architect - Fitch	**79**	61	Internal routing of services	0.649746193
Architect - GRAs	**56**	62	The colour of the vertical cladding panels	0.66751269
Services Engineer	**71**	63	The number of different sized pads to be used for the foundations	0.66751269
Cladding Supplier	**37**	64	Connection between vertical cladding & floor slab	0.685279188
BAA Project Board	**43**	65	Agree lift strategy including number and type of CIP lifts	0.715736041
Architect - GRAs	**63**	66	Finalisation of the seating areas locations and the seating arrangements (the number of seats required in public areas)	0.718274112
Client - BAA	**57**	67	The position/alignment of the airside road along/underneath the building - fine tuning of road curvature and moving some columns to accommodate bigger tolerances for drivers	0.718274112
Retail Design Consultant	**74**	68	Floor finish type for the public area: CIP Corridors	0.718274112
Retail Design Consultant	**75**	69	Floor finish type for the public area: Passenger Link bridges	0.718274112
Retail Design Consultant	**76**	70	Floor finish type for the public area: Circulation / seating areas	0.718274112
Architect - GRAs	**80**	71	Scope of lighting to ramps connecting the lounge to node 2	0.728426396
Architect - GRAs	**81**	72	Scope of lighting to public areas within lounge extension	0.728426396
QS	**55**	73	Make provision at level 5 for a WC facility (but not fit out) - for future use	0.73857868
Client - BAA	**44**	74	Sub station relocation	0.756345178
Services Engineer	**45**	75	Cold water storage	0.756345178
Services Engineer	**46**	76	Number of secondary circuits for chilled water and heating circuits	0.756345178
Client - BAA	**47**	77	Roof material to be used for entire project - considering variations of standing seam roof configuration	0.776649746
QS	**94**	78	Amount of glazing required	0.822335025
Architect - GRAs	**49**	79	Cladding to be used for the electrical substation	0.827411168
BAA Project Manager	**59**	80	The strategy in case of fire within in the building	0.840101523
Construction Manager	**64**	81	Type and scope of fire protection to structural steel work	0.840101523
Architect - Fitch	**60**	82	The smoke strategy decided upon	0.840101523
Client - BAA	**68**	83	Choice of rainwater drainage system from roof gutter	0.85786802
Client - BAA	**72**	84	Type of glazing units to be used in external cladding (type of glass and size)	0.860406091

Services Engineer	**90**	85	Bracing for existing steel frame	0.916243655
Retail Design Consultant	**88**	86	Specification of fire escape doors	1
Retail Design Consultant	**89**	87	Specification of internal doors	1
Retail Design Consultant	**92**	88	Specification of internal partitions (dividing walls between retail units etc)	1
Retail Design Consultant	**93**	89	Specification of internal partitions (dividing walls for escape units)	1

Table H.1 – List of System / Sub-System Level Design Decisions for the Gatwick Case Study by Order of Decision Occurrence

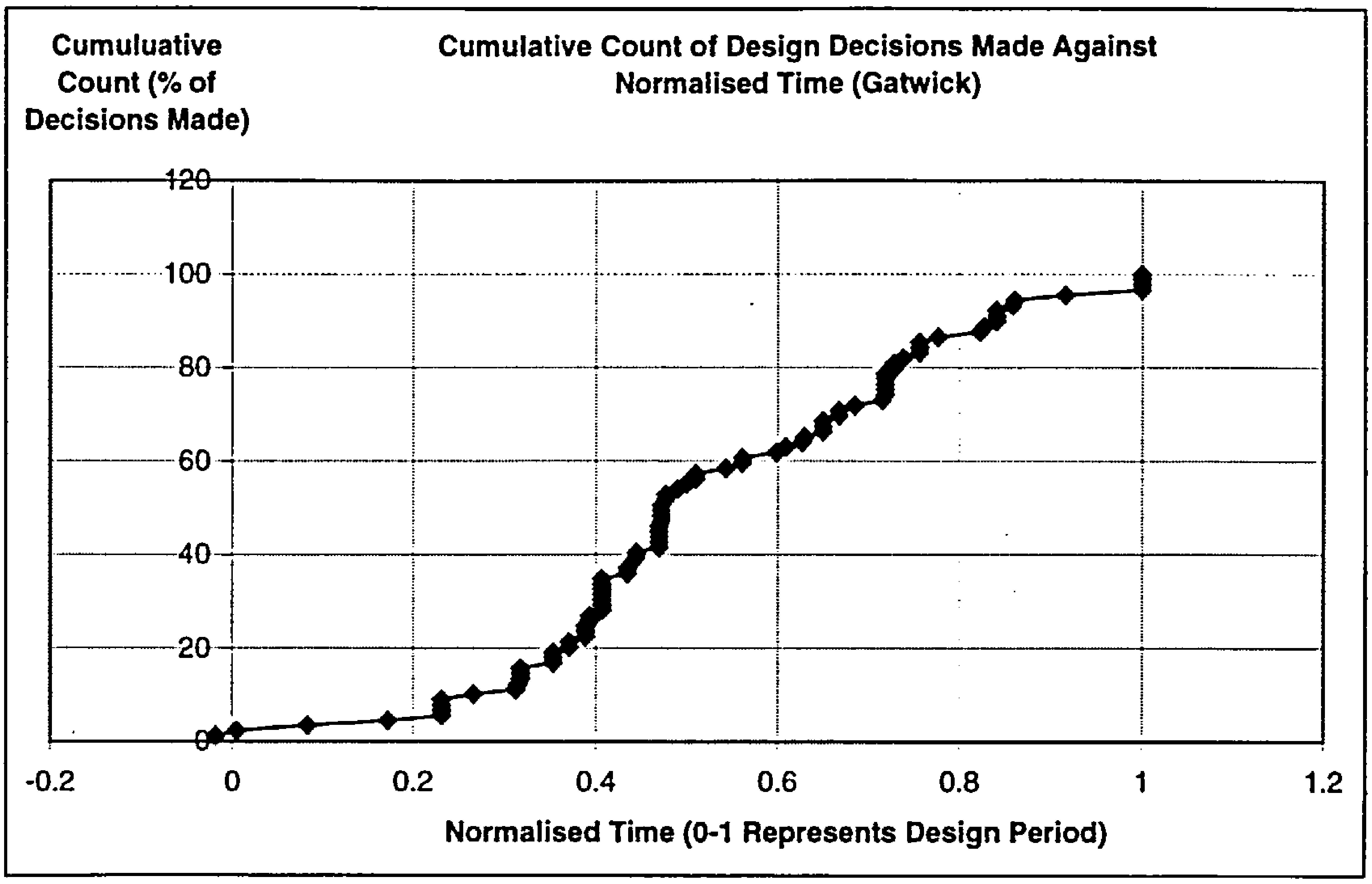


Figure H.1 - Cumulative Count of Design Decisions Made Against Normalised Time (Gatwick)

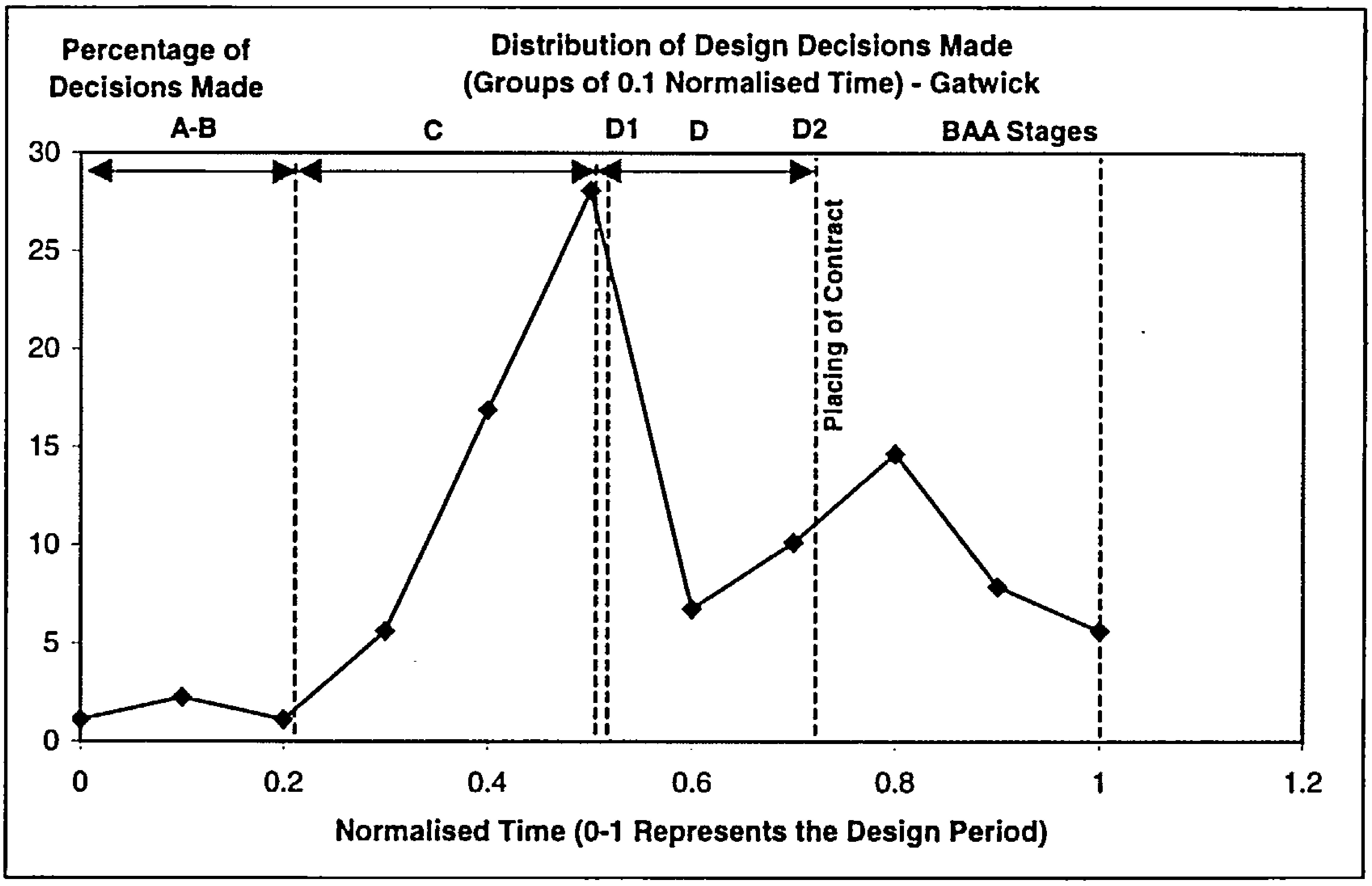


Figure H.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) - Gatwick

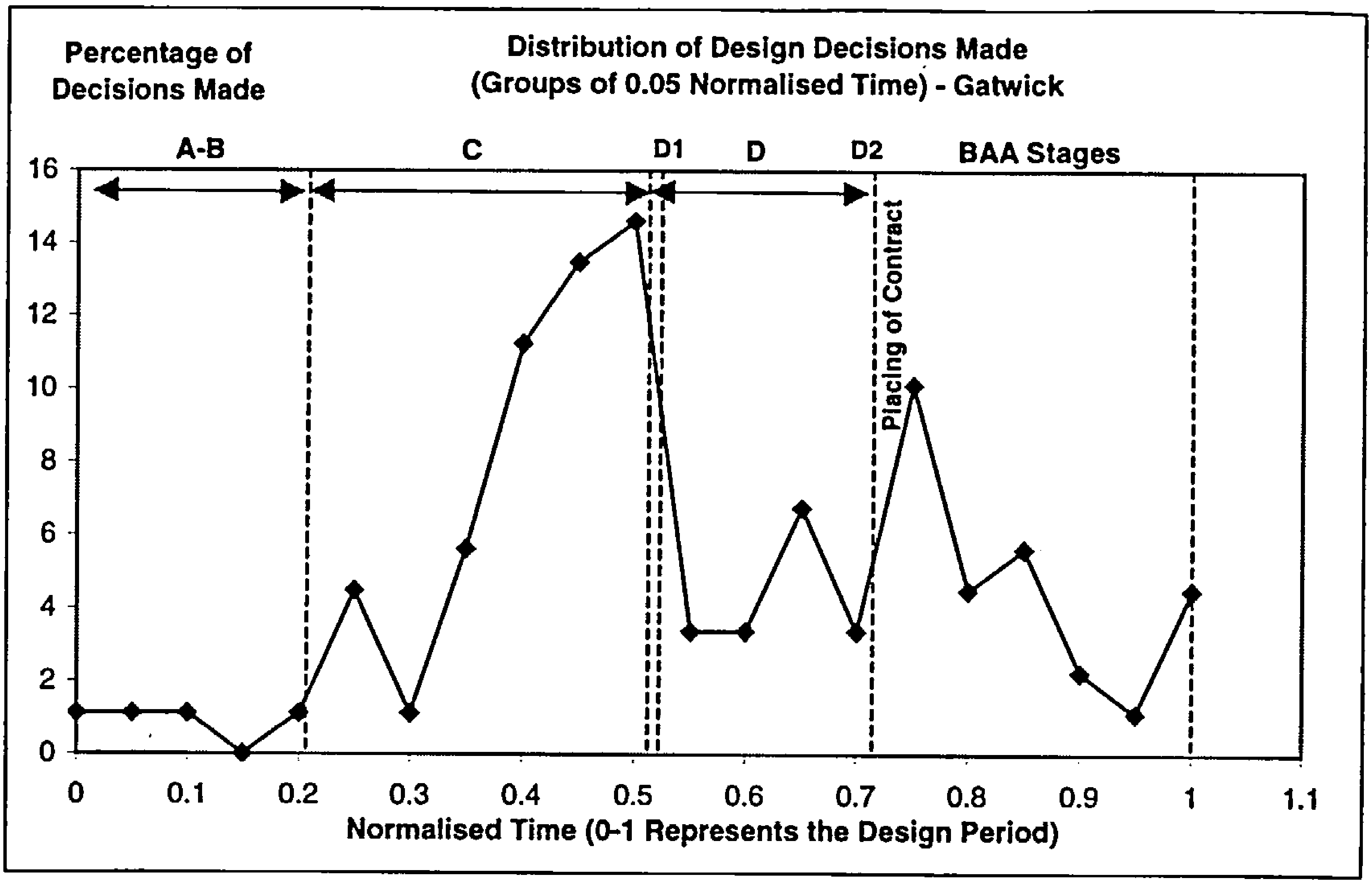


Figure H.3 - Distribution of Design Decisions (Groups of 0.05 Normalised Time) – Gatwick

Gatwick Design Team Discipline	Company
Architect	Geoffery Reid Associates
Architect	Fitch
Client	BAA
Client - Project Board (BAA)	Gatwick Airport
Construction Manager	Taylor Woodrow Construction
Framework Contractor	Rowen Structures Limited
Framework Contractor	Van Dam UK Limited
Framework Contractor	O'Rouke
Framework Contractor	Crown House Engineering
Planning Manager	Taylor Woodrow
Planning Supervisor	WS Atkins
Project Manager (BAA)	BAA
Project Manager - Fitout Contractor	TCL
Cost Stylist (QS)	EC Harris
Retail Design Consultant	Fitch
Service Engineer	WSP
Structural Engineer	HJT

Table H.2 – Design Team (Gatwick)

Decision Maker	Decision Number	Decision Order	Gatwick Design Decision Made	Normalised Time
Architect - Fitch	82	11	To use mechanically assisted ventilation and cooling	0.31472081
Architect - Fitch	9	15	Location of Commercially Important Persons (CIP) location	0.35279188
Architect - Fitch	16	20	Floor levels for level 3 & level 4	0.38832487
Architect - Fitch	39	25	Decided general location of sub station (not specific place) just the level	0.40609137
Architect - Fitch	40	26	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)	0.40609137
Architect - Fitch	78	34	Incoming service provision (routing of) electricity, water, drainage	0.43908629
Architect - Fitch	85	48	Decision to have a goods lift located adjacent to the west stair	0.48984772
Architect - Fitch	86	56	Routes for foul and surface water drainage	0.60913706
Architect - Fitch	65	57	To use an alternative supplier for the bonded store hoist (lift for bonded store - store for duty free area)	0.62690355
Architect - Fitch	79	59	Internal routing of services	0.64974619
Architect - Fitch	60	80	The smoke strategy decided upon	0.84010152
Architect - GRAs	1	5	Floor finish zone - none structural element	0.23096447
Architect - GRAs	10	16	Pier 2/3 access ramp & transfers configuration	0.35279188
Architect - GRAs	18	27	Wing Tip Clearances to the end of building - is SW corner too close to wing tip of aircraft	0.40609137
Architect - GRAs	20	32	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction	0.43401015
Architect - GRAs	35	37	Fire compartmentation for whole of project fixity SC4	0.46954315
Architect - GRAs	56	62	The colour of the vertical cladding panels	0.66751269
Architect - GRAs	63	66	Finalisation of the seating areas locations and the seating arrangements (the number of seats required in public areas)	0.71827411
Architect - GRAs	80	71	Scope of lighting to ramps connecting the lounge to node 2	0.7284264
Architect - GRAs	81	72	Scope of lighting to public areas within lounge extension	0.7284264
Architect - GRAs	49	79	Cladding to be used for the electrical substation	0.82741117
BAA Project Board	3	6	Building height	0.23096447
BAA Project Board	33	46	**Main airside road realignment**	**0.47715736**
BAA Project Board	42	53	Allow the BAA project process to be changed to allow works to commence before the required level of cost certainty achieved.	0.56091371
BAA Project Board	48	58	This is the detail of the connection between vertical cladding and the floor slab at columns - interface issue between two packages using different contractors - see fixity no. 37 for general statement	0.62944162

BAA Project Board	43	65	Agree lift strategy including number and type of CIP lifts	0.71573604
BAA Project Manager	4	7	Building structure	0.23096447
BAA Project Manager	6	12	Plant locations	0.31725888
BAA Project Manager	7	13	Main extension roof profile	0.31725888
BAA Project Manager	12	18	Location of new WC facilities	0.37055838
BAA Project Manager	14	21	SW corner building perimeter - build in existing space	0.38832487
BAA Project Manager	21	33	Level 5 finish floor level	0.43401015
BAA Project Manager	25	38	Smoke Strategy (ME3) for levels 3 and 4/5	0.46954315
BAA Project Manager	34	39	Roof level	0.46954315
BAA Project Manager	29	42	Retail Storage Area Locations and Access	0.47208122
BAA Project Manager	30	43	Location of CIP Lounges and associated access routes	0.47208122
BAA Project Manager	59	81	The strategy in case of fire within in the building	0.84010152
Cladding Supplier	37	64	Connection between vertical cladding & floor slab	0.68527919
Client - BAA	87	1	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2	-0.0177665
Client - BAA	15	22	Escape routes	0.38832487
Client - BAA	28	44	Retail space layout	0.47208122
Client - BAA	31	45	**Number and location of seating areas**	**0.47208122**
Client - BAA	62	50	Passenger segregation within the area affected by departures lounge project	0.51015228
Client - BAA	73	54	Whether to screed (floor finish issue) tenanted areas or not	0.56091371
Client - BAA	83	60	Specific requirements for CCTV	0.64974619
Client - BAA	84	61	Specific requirements for swipe card entry points	0.64974619
Client - BAA	57	67	The position/alignment of the airside road along/underneath the building - fine tuning of road curvature and moving some columns to accommodate bigger tolerances for drivers	0.71827411
Client - BAA	44	74	Sub station relocation	0.75634518
Client - BAA	47	77	Roof material to be used for entire project - considering variations of standing seam roof configuration	0.77664975
Client - BAA	68	83	Choice of rainwater drainage system from roof gutter	0.85786802
Client - BAA	72	84	Type of glazing units to be used in external cladding (type of glass and size)	0.86040609
Construction Manager	64	82	Type and scope of fire protection to structural steel work	0.84010152
Framework Contractor	41	55	Dimension between gridline and cladding.	0.59898477
QS	53	4	Basic floor plate and space usage	0.17258883
QS	24	35	Power strategy (me2) LV distribution	0.44416244
QS	61	51	Concept stage wayfinding system	0.51015228
QS	55	73	Make provision at level 5 for a WC facility (but not fit out) - for future use	0.73857868

QS	**94**	78	Amount of glazing required	0.82233503
Retail Design Consultant	**74**	68	Floor finish type for the public area: CIP Corridors	0.71827411
Retail Design Consultant	**75**	69	Floor finish type for the public area: Passenger Link bridges	0.71827411
Retail Design Consultant	**76**	70	Floor finish type for the public area: Circulation / seating areas	0.71827411
Retail Design Consultant	**88**	86	Specification of fire escape doors	1
Retail Design Consultant	**89**	87	Specification of internal doors	1
Retail Design Consultant	**92**	88	Specification of internal partitions (dividing walls between retail units etc)	1
Retail Design Consultant	**93**	89	Specification of internal partitions (dividing walls for escape units)	1
Services Engineer	**77**	2	Scope of service provision for retail / catering units	0.00507614
Services Engineer	**54**	10	Type of material for the external face of the cladding for the entire extension	0.31218274
Services Engineer	**50**	14	Selecting the grid dimensions	0.31725888
Services Engineer	**8**	17	**Service riser location**	**0.35279188**
Services Engineer	**51**	23	To have a 24m span over the air side road - the road goes underneath the extension on the South West corner	0.39340102
Services Engineer	**52**	24	Locations of the structural columns with respect to the existing passenger link bridges taking departing and arriving passengers from the pier to the terminal	0.39340102
Services Engineer	**17**	28	Service riser location {See number 8 same details}	0.40609137
Services Engineer	**19**	29	Level 5 WC location {See no. 12}	0.40609137
Services Engineer	**23**	30	**Fix Specialist systems strategy including fire alarms, CCTV, door access, FIS public address**	**0.40609137**
Services Engineer	**38**	31	How to supply the electrical power supply of the building (2.4MVA) - covers all uses within the extension	0.40609137
Services Engineer	**22**	36	Mechanical Strategy (ME1 on Project Process)	0.44416244
Services Engineer	**26**	40	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas	0.46954315
Services Engineer	**27**	41	Public Health primary services routes	0.46954315
Services Engineer	**70**	49	The type of foundation to be used for the extension	0.5
Services Engineer	**71**	63	The number of different sized pads to be used for the foundations	0.66751269
Services Engineer	**45**	75	Cold water storage	0.75634518
Services Engineer	**46**	76	Number of secondary circuits for chilled water and heating circuits	0.75634518
Services Engineer	**90**	85	Bracing for existing steel frame	0.91624365
Structural Engineer	**69**	3	Type of material for frame	0.08375635

Structural Engineer	**2**	8	Floor finish materials	0.23096447
Structural Engineer	**5**	9	Floor slab thickness set at 150mm	0.26649746
Structural Engineer	**11**	19	Cladding module size	0.37055838
Structural Engineer	**32**	47	Type of roof liner & support	0.47715736
Structural Engineer	**36**	52	Were is the front edge of the building	0.54314721

Table H.3 – List of System / Sub-System Level Design Decisions for the Gatwick Case Study by Order of Decision Maker

Decision Number	Gatwick Decisions That The Architect Was Involved In Making
2	Floor finish materials
3	Building height
4	Building structure
5	Floor slab thickness set at 150mm
6	Plant locations
7	Main extension roof profile
8	**Service riser location**
11	Cladding module size
12	Location of new WC facilities
14	SW corner building perimeter - build in existing space
15	Escape routes
19	Level 5 WC location (See no. 12)
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction
21	Level 5 finish floor level
24	Power strategy (me2) LV distribution
25	Smoke Strategy (ME3) for levels 3 and 4/5
26	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas
27	Public Health primary services routes
28	Retail space layout
29	Retail storage Area Locations and Access
30	Location of CIP Lounges and associated access routes
31	**Number and location of seating areas**
32	Type of roof liner & support
33	**Main airside road realignment**
34	Roof level
36	Were is the front edge of the building
37	Connection between vertical cladding & floor slab
40	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)
41	Dimension between gridline and cladding.
43	Agree lift strategy including number and type of CIP lifts
44	Sub station relocation
47	Roof material to be used for entire project - considering variations of standing seam roof configuration
50	Selecting the grid dimensions
51	To have a 24m span over the air side road - the road goes underneath the extension on the South West corner
52	Locations of the structural columns with respect to the existing passenger link bridges taking departing and arriving passengers from the pier to the terminal
53	Basic floor plate and space usage
54	Type of material for the external face of the cladding for the entire extension
55	Make provision at level 5 for a WC facility (but not fit out) - for future use
60	The smoke strategy decided upon
61	Concept stage wayfinding system
63	Finalisation of the seating areas locations and the seating arrangements (the number of seats required in public areas)
64	Type and scope of fire protection to structural steel work
68	Choice of rainwater drainage system from roof gutter
74	Floor finish type for the public area: CIP Corridors
75	Floor finish type for the public area: Passenger Link bridges
76	Floor finish type for the public area: Circulation / seating areas
79	Internal routing of services

83	Specific requirements for CCTV
84	Specific requirements for swipe card entry points
87	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2
88	Specification of fire escape doors
89	Specification of internal doors
90	Bracing for existing steel frame
92	Specification of internal partitions (dividing walls between retail units etc)
93	Specification of internal partitions (dividing walls for escape units)
94	Amount of glazing required

Table H.4 - List of System / Sub-System Level Design Decisions that the Architect was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Client's Agent Was Involved In Making
1	Floor finish zone - none structural element
2	Floor finish materials
3	Building height
4	Building structure
8	**Service riser location**
9	Location of Commercially Important Persons (CIP) location
10	Pier 2/3 access ramp & transfers configuration
12	Location of new WC facilities
15	Escape routes
16	Floor Levels for level 3 & level 4
18	Wing Tip Clearances to the end of building - is SW corner too close to wing tip of aircraft
19	Level 5 WC location {See no. 12}
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction
28	Retail space layout
29	Retail storage area locations and access
30	Location of CIP Lounges and associated access routes
31	**Number and location of seating areas**
33	**Main airside road realignment**
34	Roof level
36	Were is the front edge of the building
43	Agree lift strategy including number and type of CIP lifts
44	Sub station relocation
45	Cold water storage
47	Roof material to be used for entire project - considering variations of standing seam roof configuration
73	Whether to screed (floor finish issue) tenanted areas or not
74	Floor finish type for the public area: CIP Corridors
75	Floor finish type for the public area: Passenger Link bridges
76	Floor finish type for the public area: Circulation / seating areas

Table H.5 - List of System / Sub-System Level Design Decisions that the Client's Agent was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The End User Was Involved In Making
3	Building height
33	**Main airside road realignment**
38	How to supply the electrical power supply of the building (2.4MVA) - covers all uses within the extension
61	Concept stage wayfinding system
62	Passenger segregation within the area affected by departures lounge project
63	Finalisation of the seating areas locations and the seating arrangements (the number of seats required in public areas)

Table H.6 - List of System / Sub-System Level Design Decisions that the End User was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Highways Engineer Was Involved In Making
33	**Main airside road realignment**
36	Were is the front edge of the building
57	The position/alignment of the airside road along/underneath the building - fine tuning of road curvature and moving some columns to accommodate bigger tolerances for drivers

Table H.7 - List of System / Sub-System Level Design Decisions that the Highways Engineer was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Planning Supervisor Was Involved In Making
33	**Main airside road realignment**

Table H.8 - List of System / Sub-System Level Design Decisions that the Planning Supervisor was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Project Manager Was Involved In Making
1	Floor finish zone - none structural element
2	Floor finish materials
3	Building height
5	Floor slab thickness set at 150mm
8	**Service riser location**
9	Location of Commercially Important Persons (CIP) location
10	Pier 2/3 access ramp & transfers configuration
11	Cladding module size
14	SW corner building perimeter - build in existing space
16	Floor Levels for level 3 & level 4
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction
26	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas
33	**Main airside road realignment**
34	Roof level
36	Were is the front edge of the building
37	Connection between vertical cladding & floor slab
38	How to supply the electrical power supply of the building (2.4MVA) - covers all uses within the extension
39	Decided general location of sub station (not specific place) just the level
40	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)

42	Allow the BAA project process to be changed to allow works to commence before the required level of cost certainty achieved.
43	Agree lift strategy including number and type of CIP lifts
45	Cold water storage
46	Number of secondary circuits for chilled water and heating circuits
49	Cladding to be used for the electrical substation
50	Selecting the grid dimensions
51	To have a 24m span over the air side road - the road goes underneath the extension on the South West corner
52	Locations of the structural columns with respect to the existing passenger link bridges taking departing and arriving passengers from the pier to the terminal
53	Basic floor plate and space usage
54	Type of material for the external face of the cladding for the entire extension
55	Make provision at level 5 for a WC facility (but not fit out) - for future use
56	The colour of the vertical cladding panels
60	The smoke strategy decided upon
61	Concept stage wayfinding system
62	Passenger segregation within the area affected by departures lounge project
64	Type and scope of fire protection to structural steel work
65	To use an alternative supplier for the bonded store hoist (lift for bonded store - store for duty free area)
66	Type of roof to be used and the detail
70	The type of foundation to be used for the extension
74	Floor finish type for the public area: CIP Corridors
75	Floor finish type for the public area: Passenger Link bridges
76	Floor finish type for the public area: Circulation / seating areas
78	Incoming service provision (routing of) electricity, water, drainage
79	Internal routing of services
80	Scope of lighting to ramps connecting the lounge to node 2
81	Scope of lighting to public areas within lounge extension
85	Decision to have a goods lift located adjacent to the west stair
86	Routes for foul and surface water drainage

Table H.9 - List of System / Sub-System Level Design Decisions that the Project Manager was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Quantity Surveyor Was Involved In Making
1	Floor finish zone - none structural element
2	Floor finish materials
3	Building height
4	Building structure
5	Floor slab thickness set at 150mm
6	Plant locations
11	Cladding module size
12	Location of new WC facilities
14	SW corner building perimeter - build in existing space
15	Escape routes
16	Floor Levels for level 3 & level 4
17	Service Riser Location (See number 8 same details)
18	Wing tip clearances to the end of building - is SW corner too close to wing tip of aircraft
19	Level 5 WC location (See no. 12)
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction

21	Level 5 finish floor level
22	Mechanical Strategy (ME1 on Project Process)
23	**Fix Specialist systems strategy including Fire Alarms CCTV Door Access FIS Public Address**
24	Power strategy (me2) LV distribution
25	Smoke Strategy (ME3) for levels 3 and 4/5
26	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas
27	Public Health primary services routes
28	Retail space layout
29	Retail storage area locations and access
30	Location of CIP Lounges and associated access routes
31	Number and location of seating areas
32	**Type of roof liner & support**
33	**Main airside road realignment**
34	Roof level
40	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)
42	Allow the BAA project process to be changed to allow works to commence before the required level of cost certainty achieved.
44	Sub station relocation
45	Cold water storage
46	Number of secondary circuits for chilled water and heating circuits
47	Roof material to be used for entire project - considering variations of standing seam roof configuration
49	Cladding to be used for the electrical substation
50	Selecting the grid dimensions
51	To have a 24m span over the air side road - the road goes underneath the extension on the South West corner
53	Basic floor plate and space usage
54	Type of material for the external face of the cladding for the entire extension
55	Make provision at level 5 for a WC facility (but not fit out) - for future use
57	The position/alignment of the airside road along/underneath the building - fine tuning of road curvature and moving some columns to accommodate bigger tolerances for drivers
61	Concept stage wayfinding system
62	Passenger segregation within the area affected by departures lounge project
64	Type and scope of fire protection to structural steel work
65	To use an alternative supplier for the bonded store hoist (lift for bonded store - store for duty free area)
66	Type of roof to be used and the detail
70	The type of foundation to be used for the extension
72	Type of glazing units to be used in external cladding (type of glass and size)
73	Whether to screed (floor finish issue) tenanted areas or not
74	Floor finish type for the public area: CIP Corridors
75	Floor finish type for the public area: Passenger Link bridges
76	Floor finish type for the public area: Circulation / seating areas
79	Internal routing of services
80	Scope of lighting to ramps connecting the lounge to node 2
81	Scope of lighting to public areas within lounge extension
85	Decision to have a goods lift located adjacent to the west stair
86	Routes for foul and surface water drainage
87	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2
94	Amount of glazing required

Table H.10 - List of System / Sub-System Level Design Decisions that the Quantity Surveyor was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Services Engineer Was Involved In Making
2	Floor finish materials
3	Building height
4	Building structure
6	Plant locations
9	Location of Commercially Important Persons (CIP) location
10	Pier 2/3 access ramp & transfers configuration
11	Cladding module size
12	Location of new WC facilities
15	Escape routes
16	Floor Levels for level 3 & level 4
19	Level 5 WC location {See no. 12}
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction
21	Level 5 finish floor level
22	Mechanical Strategy (ME1 on Project Process)
23	**Fix Specialist systems strategy including Fire Alarms CCTV Door Access FIS Public Address**
24	Power strategy (me2) LV distribution
25	Smoke Strategy (ME3) for levels 3 and 4/5
26	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas
27	Public Health Primary services routes
28	Retail space layout
30	Location of CIP Lounges and associated access routes
31	**Number and location of seating areas**
35	Fire compartmentation for whole of project fixity SC4
38	How to supply the electrical power supply of the building (2.4MVA) - covers all uses within the extension
40	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)
43	Agree lift strategy including number and type of CIP lifts
44	Sub station relocation
45	Cold water storage
46	Number of secondary circuits for chilled water and heating circuits
49	Cladding to be used for the electrical substation
50	Selecting the grid dimensions
52	Locations of the structural columns with respect to the existing passenger link bridges taking departing and arriving passengers from the pier to the terminal
53	Basic floor plate and space usage
55	Make provision at level 5 for a WC facility (but not fit out) - for future use
59	The strategy in case of fire within in the building
61	Concept stage wayfinding system
66	Type of roof to be used and the detail
68	Choice of rainwater drainage system from roof gutter
70	The type of foundation to be used for the extension
80	Scope of lighting to ramps connecting the lounge to node 2
81	Scope of lighting to public areas within lounge extension
83	Specific requirements for CCTV
84	Specific requirements for swipe card entry points
87	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2
90	Bracing for existing steel frame
94	Amount of glazing required

Table H.11 - List of System / Sub-System Level Design Decisions that the Services Engineer was Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Specialist Consultants Was Involved In Making	Specify Specialist Consultant
25	Smoke Strategy (ME3) for levels 3 and 4/5	Jeremy Gardne specialist Fire Eng., Fire officer
38	How to supply the electrical power supply of the building (2.4MVA) - covers all uses within the extension	LES
48	This is the detail of the connection between vertical cladding and the floor slab at columns - interface issue between two packages using different contractors - see fixity no. 37 for general statement	Cladding and concrete and steel work suppliers
50	Selecting the grid dimensions	Steelwork supplier
51	To have a 24m span over the air side road - the road goes underneath the extension on the South West corner	Steelwork supplier
59	The strategy in case of fire within in the building	Fire consultant
72	Type of glazing units to be used in external cladding (type of glass and size)	Cladding contractor
78	Incoming service provision (routing of) electricity, water, drainage	Airport Engineers (maintenance)
80	Scope of lighting to ramps connecting the lounge to node 2	Lighting (WSP)
81	Scope of lighting to public areas within lounge extension	Lighting (WSP)
86	Routes for foul and surface water drainage	Airport engineers / maintenance department

Table H.12 - List of System / Sub-System Level Design Decisions that Specialist Consultants were Involved in Making (Gatwick)

Decision Number	Gatwick Decisions That The Structural Engineer Was Involved In Making
1	Floor finish zone - none structural element
3	Building height
4	Building structure
6	Plant locations
7	Main extension roof profile
8	**Service riser location**
9	Location of Commercially Important Persons (CIP) location
10	Pier 2/3 access ramp & transfers configuration
12	Location of new WC facilities
14	SW corner building perimeter - build in existing space
16	Floor Levels for level 3 & level 4
18	Wing Tip Clearances to the end of building - is SW corner too close to wing tip of aircraft
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction
21	Level 5 finish floor level
24	Power strategy (me2) LV distribution
26	WC & Public Health Strategy (ME4) Mech. ventilation to toilet areas
27	Public Health primary services routes
28	Retail space layout
29	Retail storage area locations and access
30	Location of CIP Lounges and associated access routes
31	**Number and location of seating areas**
32	Type of roof liner & support
33	**Main airside road realignment**
34	Roof level
36	Were is the front edge of the building
37	Connection between vertical cladding & floor slab
40	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)

41	Dimension between gridline and cladding.
43	Agree lift strategy including number and type of CIP lifts
44	Sub station relocation
45	Cold water storage
48	This is the detail of the connection between vertical cladding and the floor slab at columns - interface issue between two packages using different contractors - see fixity no. 37 for general statement
53	Basic floor plate and space usage
57	The position/alignment of the airside road along/underneath the building - fine tuning of road curvature and moving some columns to accommodate bigger tolerances for drivers
61	Concept stage wayfinding system
62	Passenger segregation within the area affected by departures lounge project
64	Type and scope of fire protection to structural steel work
86	Routes for foul and surface water drainage
87	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2

Table H.13 - List of System / Sub-System Level Design Decisions that the Structural Engineer was involved in Making (Gatwick)

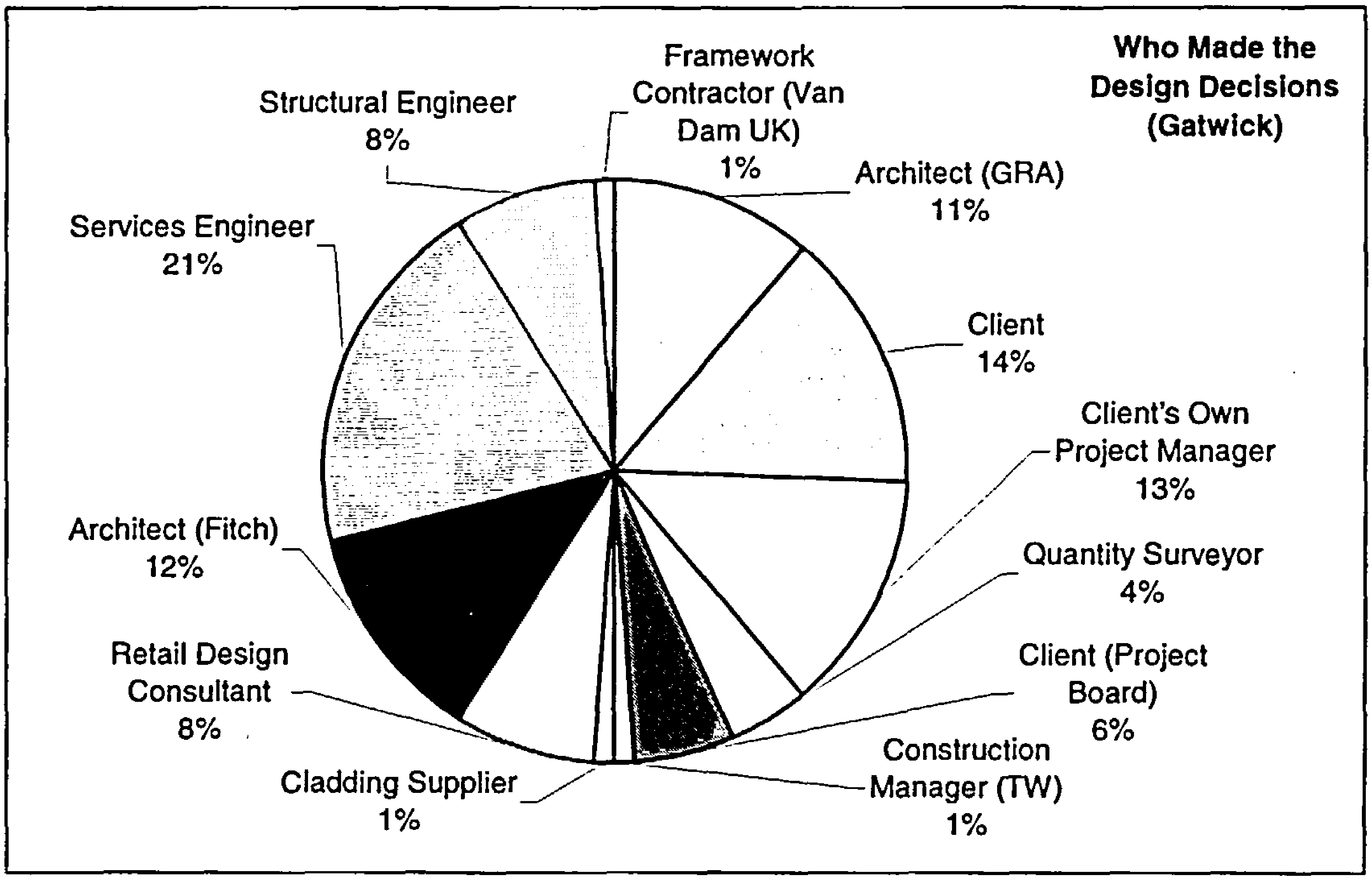


Figure H.4 – Who Made the Design Decisions (Gatwick)

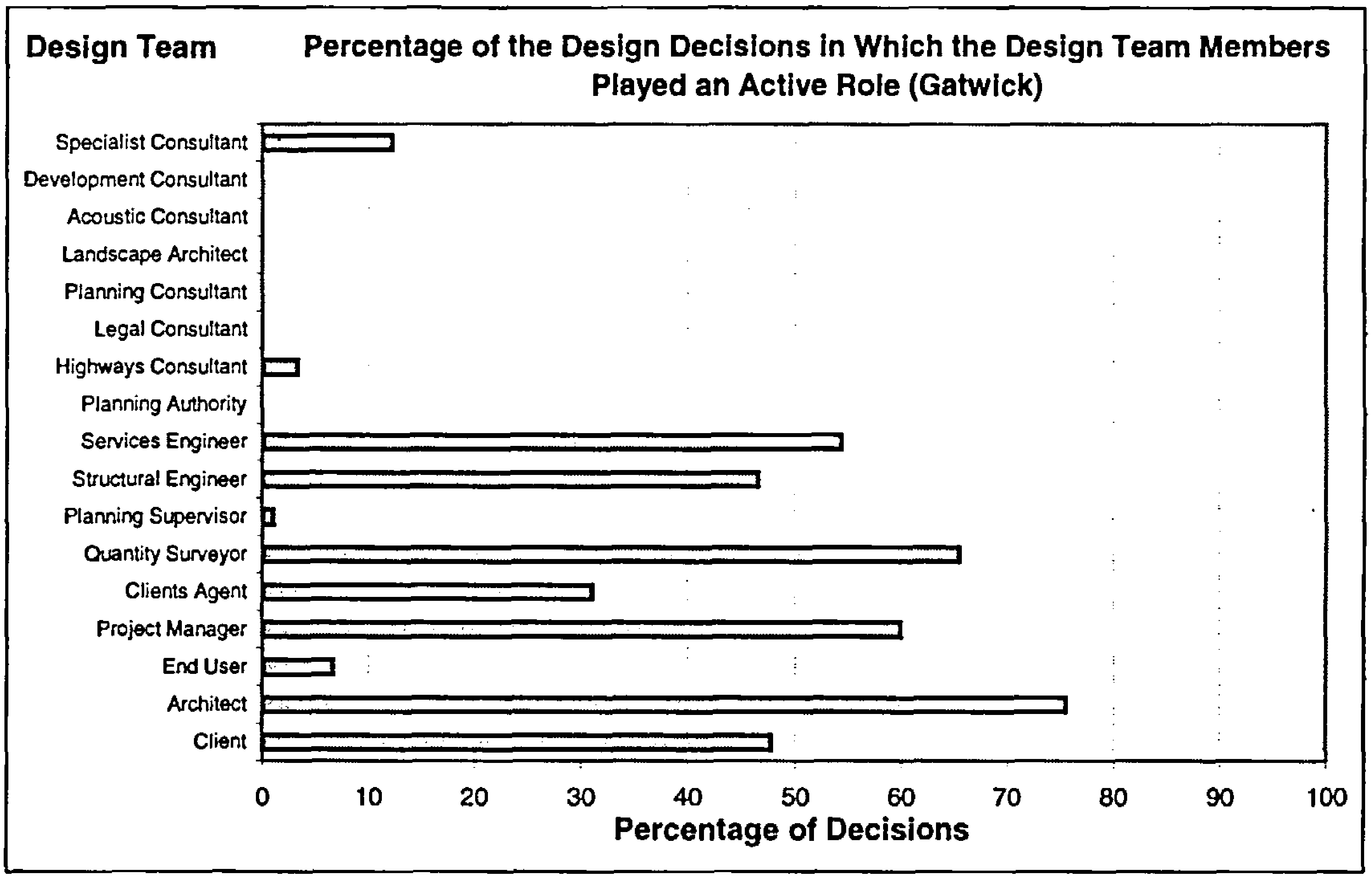


Figure H.5 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Gatwick)

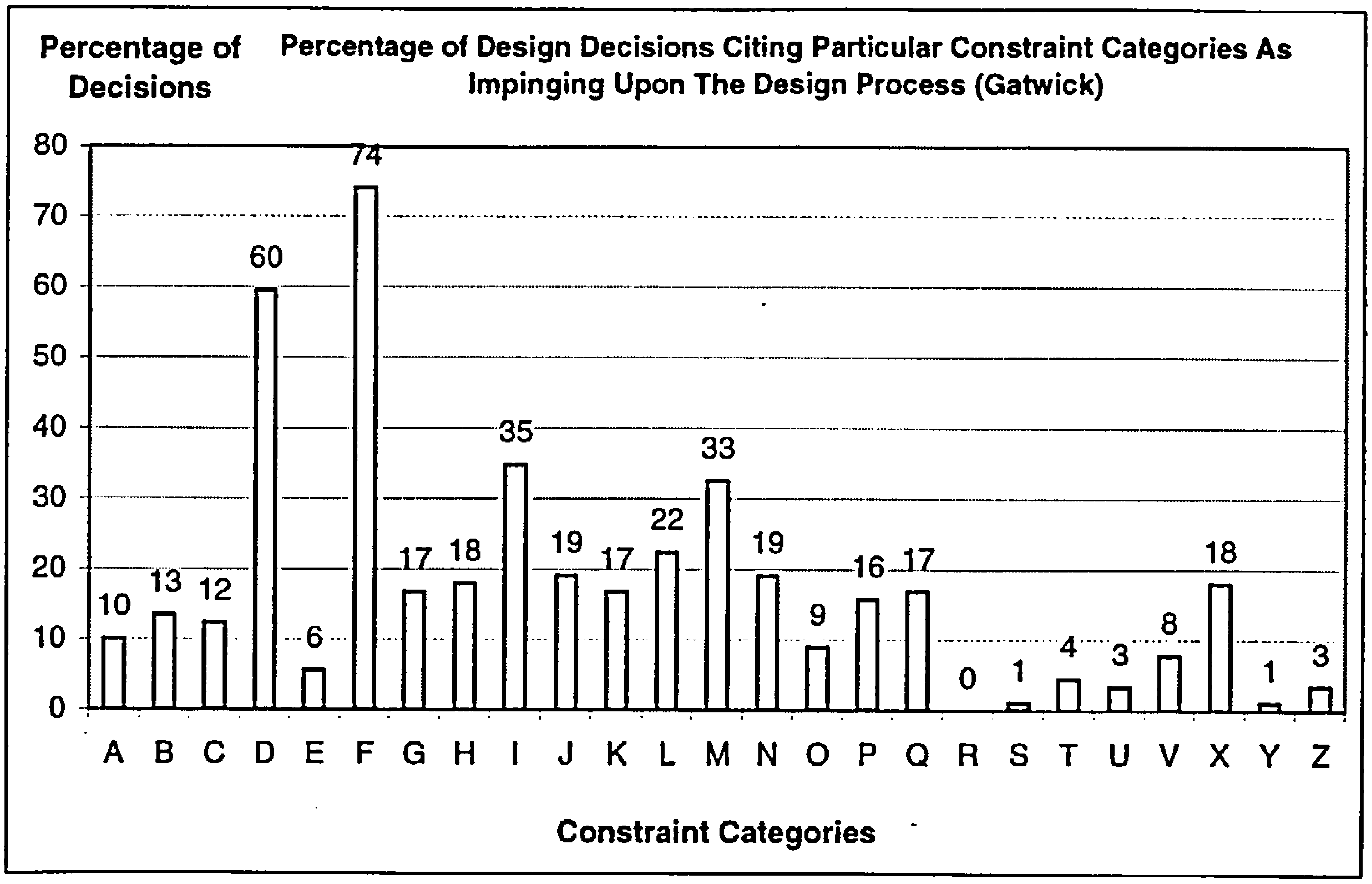


Figure H.6 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Gatwick)

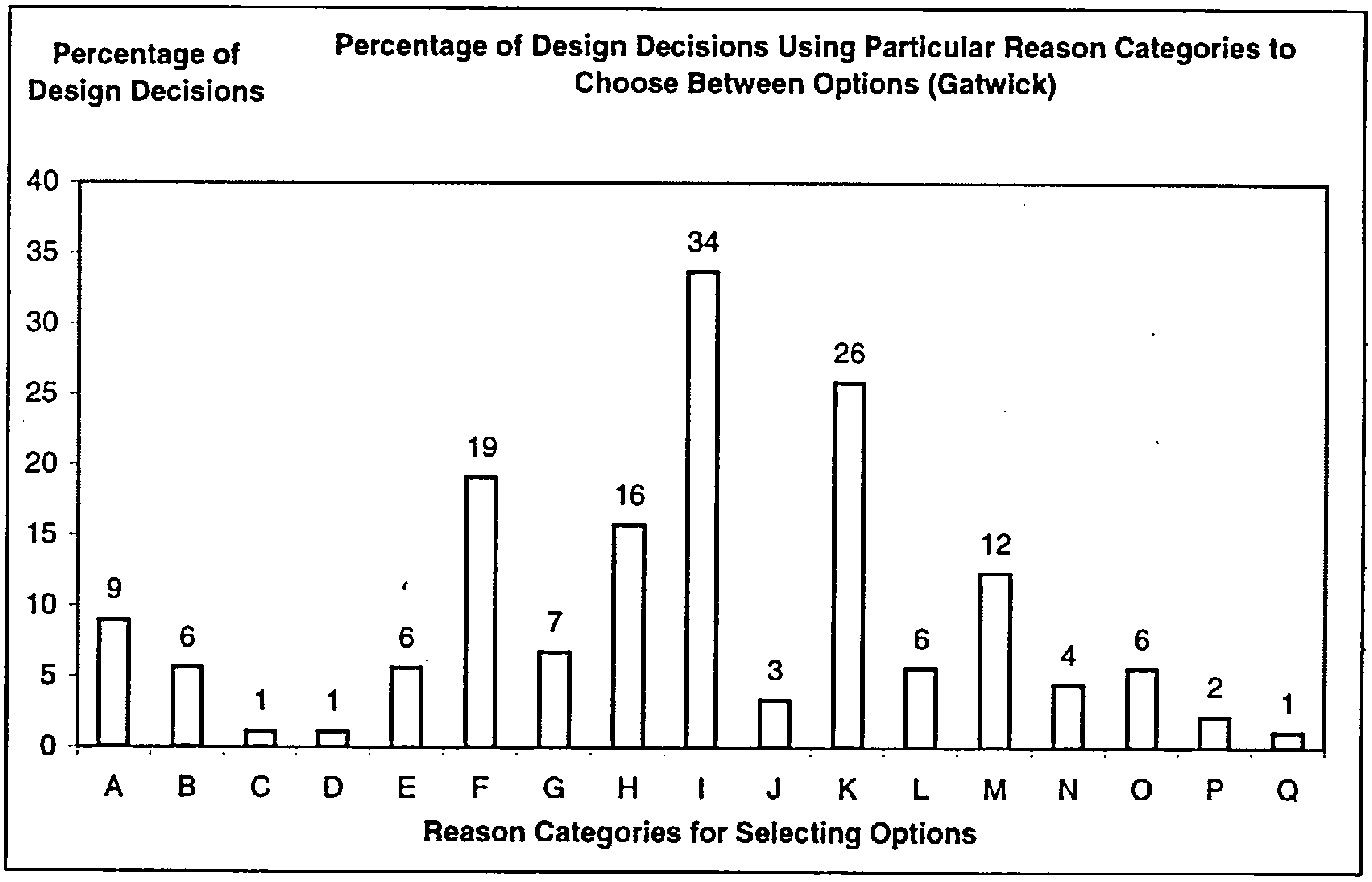


Figure H.7 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Gatwick)

Decision Number	Gatwick Decision Made	Constraints Impinging Design - Categories Cited	Reason For Selecting Options - Categories Cited
1	Floor finish zone - none structural element	A,B,C,L	A,B,C
2	Floor finish materials	B,C,D,F,H,M	D
3	Building height	D,F,I,M,O	E,F
4	Building structure	E,F,G,Q	F,G,H
5	Floor slab thickness set at 150mm	D	A
6	Plant locations	D,E,F	F,I
7	Main extension roof profile	D,F,M,Q,T	F,H,J
8	**Service riser location**	**D,F,H,J**	**F,J**
9	Location of commercially important persons (CIP) location	D,K,M,Q	H
10	Pier 2/3 access ramp & transfers configuration	B,D,F,G,H,J, K,M,Q,S	E,G,H
11	Cladding module size	D,E,F,H,I	F,H
12	Location of new WC facilities	A,B,F,K,M	K
14	SW corner building perimeter - build in existing space	D,F	I,K
15	Escape routes	D,F,L,M,N	A
16	Floor levels for level 3 & level 4	F	A,I,K
17	Service riser location {see number 8 same details}	F	
18	Wing tip clearances to the end of building - is SW corner too close to wing tip of aircraft	F	A,L
19	Level 5 WC location {see no. 12}	F	F
20	Location of SW corner riser - moved to a new position so that the access to level five CIP can be located within the area of the new construction	D,F,P	F,K
21	Level 5 finish floor level	F,I,V	I,K
22	Mechanical strategy (me1 on project process)		
23	**Fix specialist systems strategy including fire alarms CCTV door access FIS public address**	**F**	
24	Power strategy (me2) LV distribution	A,F	M
25	Smoke strategy (me3) for levels 3 and 4/5	F,K,L	I,K
26	WC & public health strategy (me4) mech. ventilation to toilet areas	K,M,N	M,N
27	Public health primary services routes	F	F
28	Retail space layout	B,F,I,K,L,M, N,Q,U,X	F,K
29	Retail storage area locations and access	F,I,X	I,K
30	Location of CIP lounges and associated access routes	I,X	K
31	**Number and location of seating areas**	**C,D,F,M,U**	**E**
32	Type of roof liner & support	D,F,N	H,K
33	**Main airside road realignment**	**D,F,G,X**	**E**
34	Roof level	D,F,I	I
35	Fire compartmentation for whole of project fixity sc4	F,L	
36	Were is the front edge of the building	D,F	E
37	Connection between vertical cladding & floor slab	D,F,H	K,O
38	How to supply the electrical power supply of the building (2.4mva) - covers all uses within the extension	F,T,M	A
39	Decided general location of sub station (not specific place) just the level	A,D,F,G	A
40	Decided that the mechanical primary plant should be open (to elements i.e. not enclosed)	A,D,H,I,P	H
41	Dimension between gridline and cladding.	D,F,K	F,H
42	Allow the BAA project process to be changed to allow works to commence before the required level of cost certainty achieved.	G,O	I,O
43	Agree lift strategy including number and type of CIP lifts	D,F,M,X	K

44	Sub station relocation	A,D,G	I,K
45	Cold water storage	D,F,L,M,Q	M
46	Number of secondary circuits for chilled water and heating circuits	A,D,E,F,L,M	B
47	Roof material to be used for entire project - considering variations of standing seam roof configuration	D,G,I,K,N,Q	K
48	This is the detail of the connection between vertical cladding and the floor slab at columns - interface issue between two packages using different contractors - see fixity no. 37 for general statement	D,F,H,O,T	B,H,O
49	Cladding to be used for the electrical substation	B,F,Q	A
50	Selecting the grid dimensions	A,B,D,F,G,I, J,X	I
51	To have a 24m span over the air side road - the road goes underneath the extension on the south west corner	D,F,J,Q	F,K,N
52	Locations of the structural columns with respect to the existing passenger link bridges taking departing and arriving passengers from the pier to the terminal	D,F,G,H,K,N ,X	G,H,I
53	Basic floor plate and space usage	D,F,G,I,J,L, M,X	G,I,O
54	Type of material for the external face of the cladding for the entire extension	D,F,H,I,J,Q	I
55	Make provision at level 5 for a WC facility (but not fit out) - for future use	F,M,N,V,X	F,I
56	The colour of the vertical cladding panels	F,I,J,L,M,Q	B,K
57	The position/alignment of the airside road along/underneath the building - fine tuning of road curvature and moving some columns to accommodate bigger tolerances for drivers	D,F,G,I,J	B,K,N
59	The strategy in case of fire within in the building	D,F,L,N	K,L,N
60	The smoke strategy decided upon	D,F,K,L,N,X	H,I,K
61	Concept stage wayfinding system	D,F,G,M,V,X	G,I
62	Passenger segregation within the area affected by departures lounge project	G,N,V,X	I,K,M
63	Finalisation of the seating areas locations and the seating arrangements (the number of seats required in public areas)	C,D,F,J,M,T	
64	Type and scope of fire protection to structural steel work	F,H,I,N,O	F,H,I
65	To use an alternative supplier for the bonded store hoist (lift for bonded store - store for duty free area)	I,J,L,N,P	I
68	Choice of rainwater drainage system from roof gutter	D,F,I,P,Q	K
69	Type of material for frame	F,I,O	I
70	The type of foundation to be used for the extension	D,F,I,O	F,I,K
71	The number of different sized pads to be used for the foundations	D,F,H,I,J	
72	Type of glazing units to be used in external cladding (type of glass and size)	D,F,I,J,L,M, N	H,M
73	Whether to screed (floor finish issue) tenanted areas or not	A,B,I,M,P,Y	I,L
74	Floor finish type for the public area: CIP corridors	I,J,K,L,P,V	J
75	Floor finish type for the public area: passenger link bridges	D,F,J,K,L,P, V,X	
76	Floor finish type for the public area: circulation / seating areas	F,G,H,J,K,L, P,Q,V	
77	Scope of service provision for retail / catering units	D,F	
78	Incoming service provision (routing of) electricity, water, drainage	D,F,I,L,P	I
79	Internal routing of services	D,F,H,I,L,P	F,G,P
80	Scope of lighting to ramps connecting the lounge to node 2	C,J,M,P	
81	Scope of lighting to public areas within lounge extension	C,J,M,P	
82	To use mechanically assisted ventilation and cooling	D,K,N	M
83	Specific requirements for CCTV	D,F,L,X	L
84	Specific requirements for swipe card entry points	D,F,L,N,X,Z	L
85	Decision to have a goods lift located adjacent to the west stair	D,F,P	I
86	Routes for foul and surface water drainage	D,F,K	H,I

87	To demolish/remove existing passenger ramp and bridge structures connecting south terminal to pier 2	D,E,G,H,I,M, X	K,M
88	Specification of fire escape doors	B,C,I,M,Z	I,M
89	Specification of internal doors	B,C,I,M,Z	I,M
90	Bracing for existing steel frame	D,F,Q	F
92	Specification of internal partitions (dividing walls between retail units etc)	B,C,H,I,M,O	I,M
93	Specification of internal partitions (dividing walls for escape units)	B,C,H,I,M,N, O	I,M
94	Amount of glazing required	C,D,I,M,N,P, Q,U	I,O,P,Q

Table H.14 - List of System / Sub-System Level Design Decisions with Corresponding ‘Constraint’ and ‘Reasons For Selection’ Categories Cited (Gatwick)

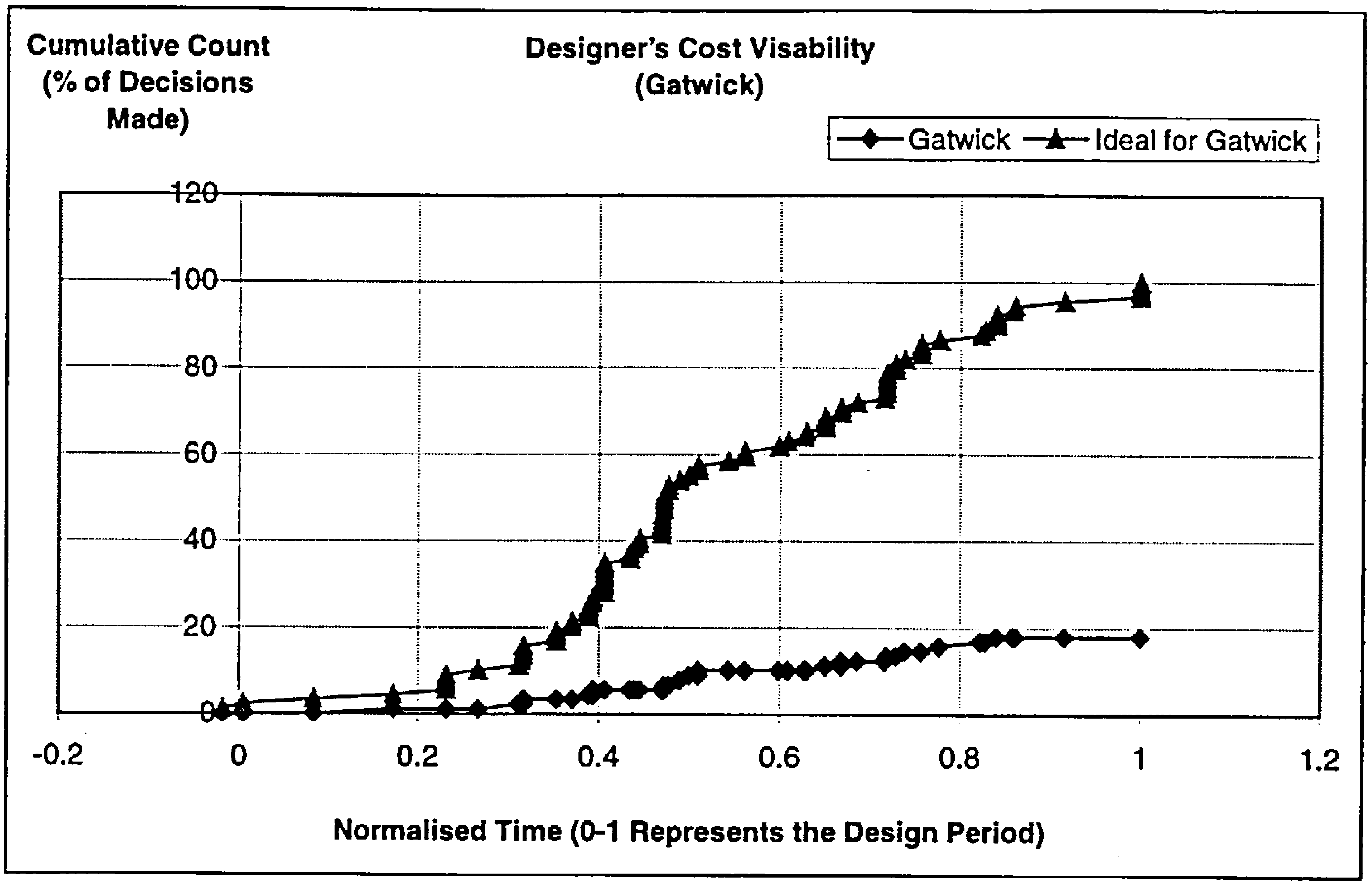


Figure H.8 – Designer's Cost Visibility (Gatwick)

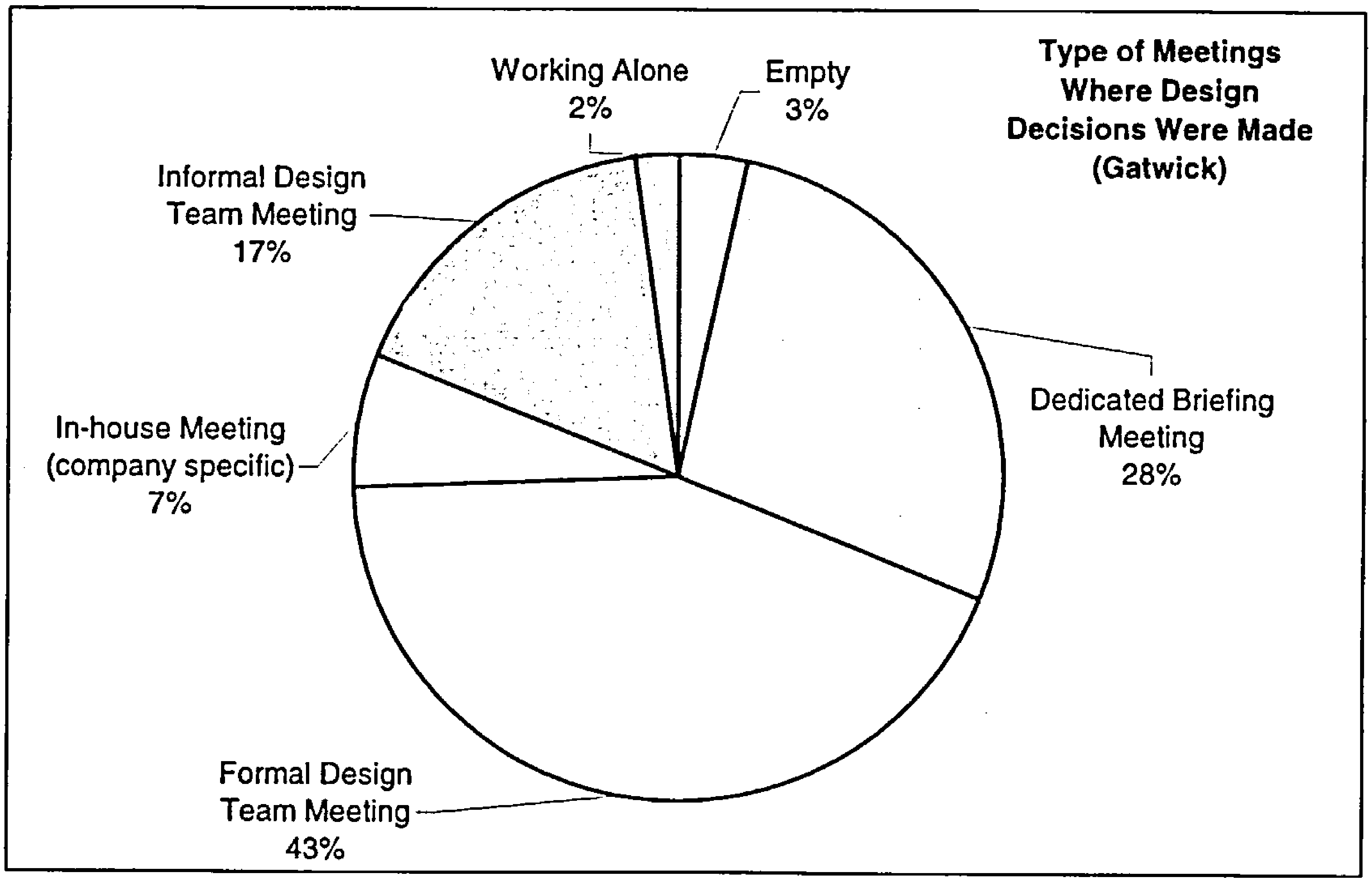


Figure H.9 – The Types of Meetings Where Design Decisions Were Made (Gatwick)

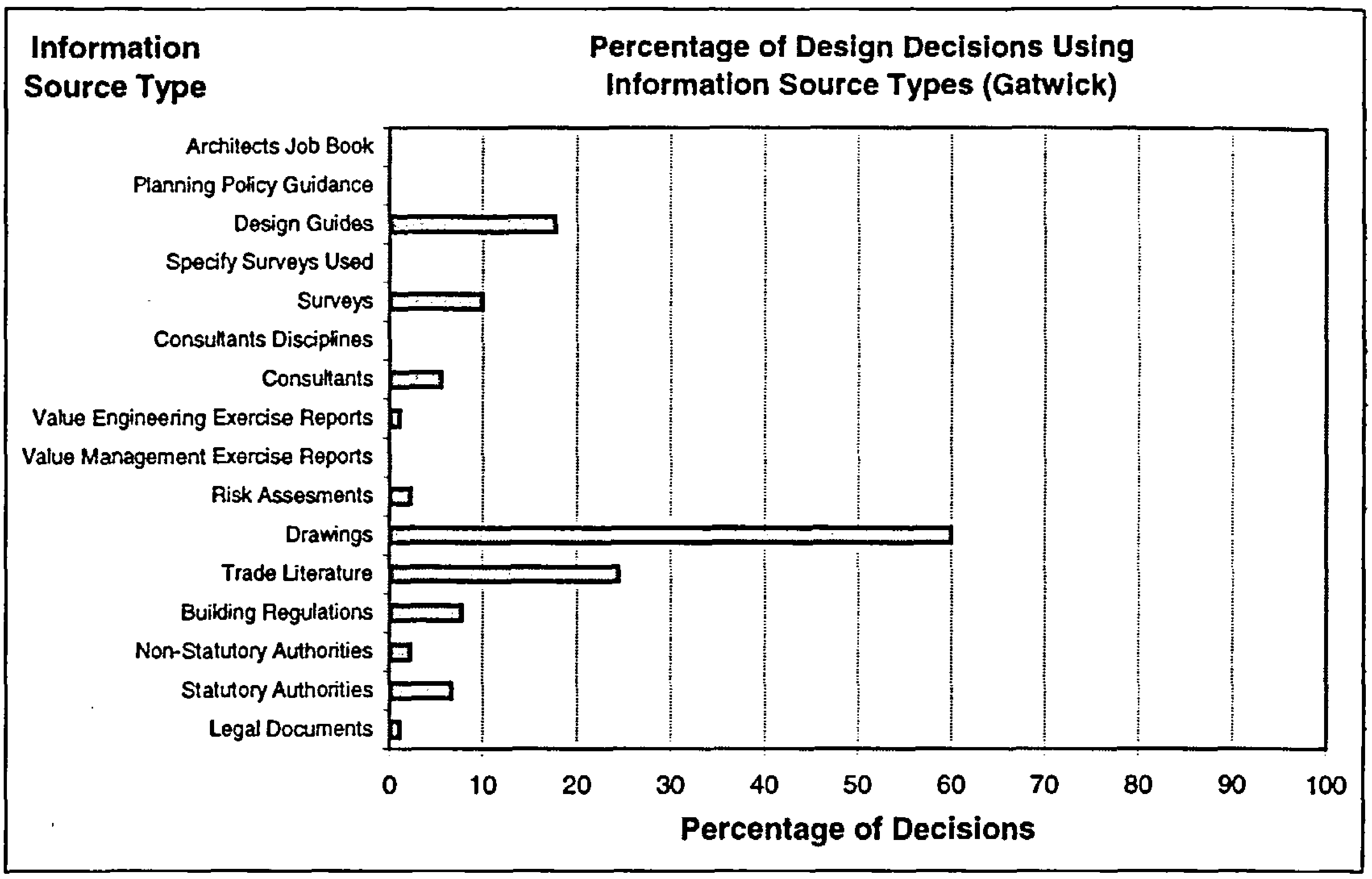


Figure H.10 – Percentage of Design Decisions Using Particular Information Source Types (Gatwick)

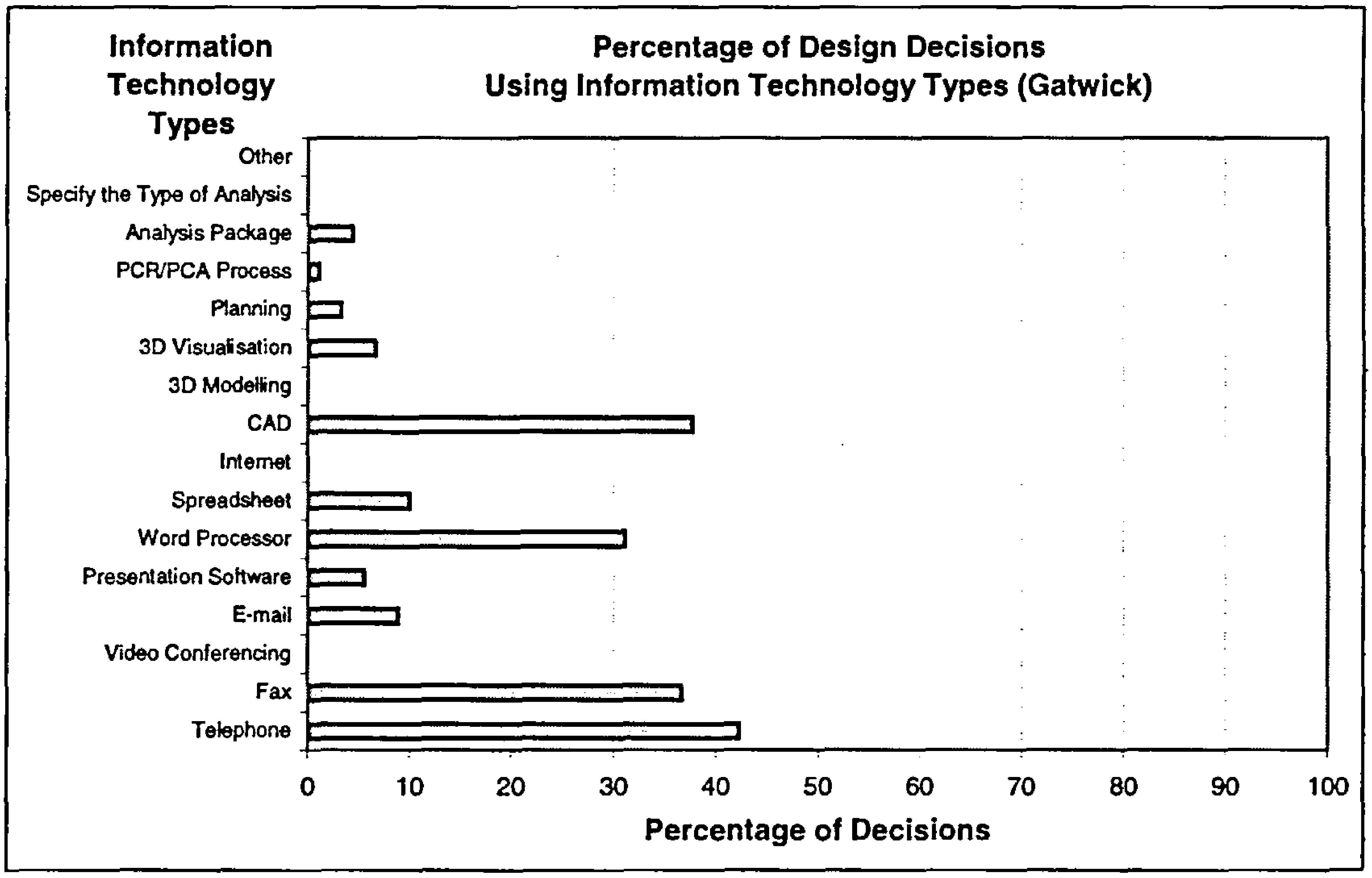


Figure H.11 – Percentage of Design Decisions Using Particular Information Technology Types (Gatwick)

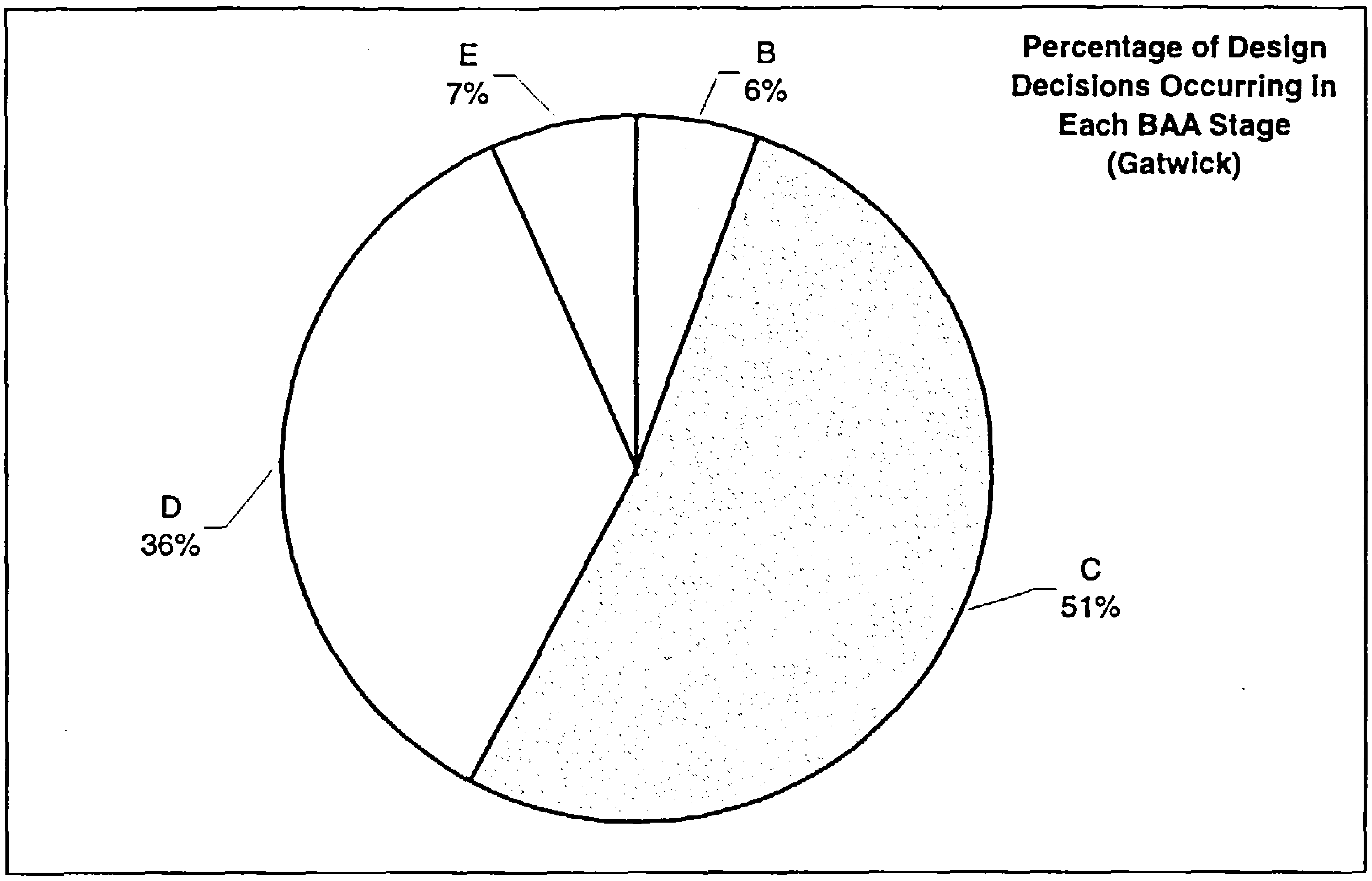


Figure H.12 – Percentage of Design Decisions Occurring in Each BAA Stage (Gatwick)

[BLANK PAGE]

APPENDIX I

List of Figures

Figure I.1 - Cumulative Count of Design Decisions Made Against Normalised Time (Bourne)...... 6

Figure I.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) – Bourne.............. 6

Figure I.3 - Distribution of Design Decisions (Groups of 0.05 Normalised Time) – Bourne............ 7

Figure I.4 – Who Made the Design Decisions (Bourne) 21

Figure I.5 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Bourne) 21

Figure I.6 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Bourne).. 22

Figure I.7 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Bourne)... 22

Figure I.8 – Designer's Cost Visibility (Bourne).. 25

Figure I.9 – The Types of Meetings Where Design Decisions Were Made (Bourne) 25

Figure I.10 – Percentage of Design Decisions Using Particular Information Source Types (Bourne).. 26

Figure I.11 – Percentage of Design Decisions Using Particular Information Technology Types (Bourne).. 26

Figure I.12 – Percentage of Design Decisions Occurring in Each RIBA Stage (Bourne) 27

List of Tables

Table I.1 – List of System / Sub-System Level Design Decisions for the Bourne Case Study by Order of Decision Occurrence 5
Table I.2 – Design Team (Chelmsford)..... 8
Table I.3 – When Each Design Team Member Joined the Project (Bourne) 9
Table I.4 – List of System / Sub-System Level Design Decisions for the Bourne Case Study by Order of Decision Maker..... 12
Table I.5 - List of System / Sub-System Level Design Decisions that the Architect was Involved in Making (Bourne) 14
Table I.6 - List of System / Sub-System Level Design Decisions that the Developer was Involved in Making (Bourne)..... 14
Table I.7 - List of System / Sub-System Level Design Decisions that the Developer's Agent was Involved in Making (Bourne) 15
Table I.8 - List of System / Sub-System Level Design Decisions that the End User was Involved in Making (Bourne) 15
Table I.9 - List of System / Sub-System Level Design Decisions that the Highways Engineer was Involved in Making (Bourne) 16
Table I.10 - List of System / Sub-System Level Design Decisions that the Landscape Architect was Involved in Making (Bourne)..... 16
Table I.11 - List of System / Sub-System Level Design Decisions that the Legal Consultant was Involved in Making (Bourne) 16
Table I.12 - List of System / Sub-System Level Design Decisions that the Planning Authority was Involved in Making (Bourne) 16
Table I.13 - List of System / Sub-System Level Design Decisions that the Planning Supervisor was Involved in Making (Bourne)..... 16
Table I.14 - List of System / Sub-System Level Design Decisions that the Project Manager was Involved in Making (Bourne) 17
Table I.15 - List of System / Sub-System Level Design Decisions that the Quantity Surveyor was Involved in Making (Bourne) 18
Table I.16 - List of System / Sub-System Level Design Decisions that the Services Engineer was Involved in Making (Bourne) 19
Table I.17 - List of System / Sub-System Level Design Decisions that Specialist Consultants were Involved in Making (Bourne) 19
Table I.18 - List of System / Sub-System Level Design Decisions that the Structural Engineer was Involved in Making (Bourne) 20
Table I.19 - List of System / Sub-System Level Design Decisions with Corresponding 'Constraint' and 'Reasons For Selection' Categories Cited (Bourne)..... 24

Decision Maker	Decision Number	Decision Order	Bourne Design Decision Made	Normalised Time
Architect	9	1	Extent of demolition on site - buildings at ground level	0
Developer	10	2	Extent of the ground level demolition	0
Highways Engineer	73	3	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)	0.083402147
Architect	2	4	Structural bay / grid dimensions	0.252683732
Architect	5	5	Footprint of initial building design	0.252683732
Architect	1	6	Selection of the frame system / material	0.252683732
Developer	72	7	Customer & staff car parking surface material selection	0.279933939
Architect	65	8	Landscaping approach (decision for 30k budget)	0.292320396
Developer	57	9	Selection of lift system for loading bay	0.292320396
Developer	18	10	Selection of the roof system / material	0.29314616
Developer	24	11	Selection of internal skin material	0.29314616
Developer	16	12	Arrangement of the roof structure	0.29314616
Developer	15	13	Selection of the roof structure type	0.29314616
Developer	19	14	Arrangement of the roof system / profile	0.29314616
Developer	23	15	Selection of external skin system / material	0.29314616
Developer	34	16	Type of fire compartmentation to be used (partition wall - between sales and domestic)	0.294797688
Developer	33	17	Type of internal partition wall used (to define areas of space for different uses)	0.294797688
Structural Engineer	67	18	Surface finish of service yard	0.294797688
Client - Sainsbury	82	19	Position of service bays	0.569777044
Architect	70	20	Specifying the amount of glazing required	0.596201486
Client - Sainsbury	63	21	CCTV (internally only)	0.596201486
Client - Sainsbury	64	22	Telecommunications specification (telephones, computer lines, Granada satellite system)	0.596201486
Architect	71	23	Customer & staff car parking location	0.597853014
Structural Engineer	12	24	Selection of substructure system / material	0.652353427
Structural Engineer	30	25	Selection of the floor system / configuration	0.665565648
Contractor	31	26	Selection floor finish (concrete floor finish - not final finish)	0.684558216
Architect	3	27	Configuration / Layout of the structure	0.711808423
Services Engineer	77	28	Positioning the service meter cupboard	0.743187448
Structural Engineer	11	29	Extent of the below ground level demolition	0.770437655
Architect	25	30	Decision to have an acoustic screen around exposed plant	0.777869529
Client - Sainsbury	74	31	Location of plant room	0.780346821
Services Engineer	41	32	Configuration of ventilation system	0.780346821
Services Engineer	42	33	Location of the substation	0.780346821
Services Engineer	40	34	Type of ventilation system selected	0.780346821
Architect	80	35	Rendered panel in external skin	0.787778695

Client - Sainsbury	**36**	36	The organisation of internal space	0.787778695
Client - Sainsbury	**75**	37	Decision to have open / closed plant	0.792733278
Client - Sainsbury	**66**	38	Location of service yard	0.794384806
Client - Sainsbury	**58**	39	Location of the lift system	0.79521057
Fitout Architect	**35**	40	Type of fire compartmentation to be used (partition wall - between sales and domestic)	0.796862097
Architect	**20**	41	Decided to include a pedestrian walkway canopy	0.820809249
Contractor	**22**	42	Selection of the roof system / material for the plant room	0.820809249
Architect	**26**	43	Arrangement of external skin - depth of wall (size of cavity)	0.824938068
Architect	**27**	44	Selection of Insulation type	0.829066887
Services Engineer	**46**	45	Gas capacity	0.829066887
Services Engineer	**47**	46	Routing of water supply (decided to route with other services)	0.829066887
Services Engineer	**48**	47	Water capacity	0.829066887
Services Engineer	**45**	48	Routing of gas supply (decided to route with other services)	0.829066887
Contractor	**81**	49	Selection of insulation material for the roof	0.833195706
Client - Sainsbury	**13**	50	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure	0.843930636
Contractor	**83**	51	Dimension between external skin and gridline	0.85136251
Architect	**7**	52	Specification of the building footprint / configuration	0.857142857
Client - Sainsbury	**6**	53	Final footprint for building design	0.857142857
Architect	**76**	54	Paving material selection	0.863748968
Architect	**55**	55	Selection of car parking lighting system	0.863748968
Client - Sainsbury	**59**	56	External signage configuration	0.864574732
Architect	**28**	57	External skin - architectural features	0.867052023
Architect	**29**	58	Selection of material for external skin	0.867052023
Client - Sainsbury	**17**	59	To include wind catchers in the roof system	0.867877787
Fitout Architect	**79**	60	Specification of internal doors	0.868703551
Fitout Architect	**32**	61	Selection of the final floor finish	0.87283237
Contractor	**8**	62	Cut and fill exercise required to level off the site (store level on site)	0.875309661
Structural Engineer	**4**	63	Bracing to steel frame (amount and arrangement)	0.878612717
Fitout Architect	**62**	64	Escape routes defined	0.886870355
Fitout Architect	**60**	65	Fire protection for structural steel	0.886870355
Fitout Architect	**61**	66	Fire compartmentation	0.886870355
Services Engineer	**44**	67	Routing of electrical services	0.887696119
Fitout Architect	**78**	68	Specification of public access doors	0.892650702

Structural Engineer	**52**	69	Routing of soiled water drain (roof and landscape water run off)	0.903385632
Structural Engineer	**53**	70	Capacity of soiled water drain (roof and landscape water run off)	0.903385632
Structural Engineer	**51**	71	Capacity of foul water drain	0.903385632
Structural Engineer	**50**	72	Routing of foul water drain	0.903385632
Contractor	**49**	73	Selection of roof drainage system	0.904211396
Client - Sainsbury	**68**	74	The decision to include recycling facilities on the service road - i.e. to service yard	0.915772089
Structural Engineer	**14**	75	Decision to incorporate a gas permeable membrane into the substructure	0.916597853
Architect	**54**	76	Car park drainage system	0.918249381
Architect	**37**	77	Specification of means of escape doors	0.921552436
Architect	**38**	78	Specification of service doors	0.937241949
Services Engineer	**56**	79	Selection of store perimeter lighting	0.944673823
Architect	**69**	80	Selection of the type of windows / glazing	0.9611891
Architect	**39**	81	Specification of service yard gate	0.977704377
Architect	**84**	82	Enclosure type for substation	1
Developer's QS	**43**	83	Capacity of the substation	1.082576383

Table I.1 – List of System / Sub-System Level Design Decisions for the Bourne Case Study by Order of Decision Occurrence

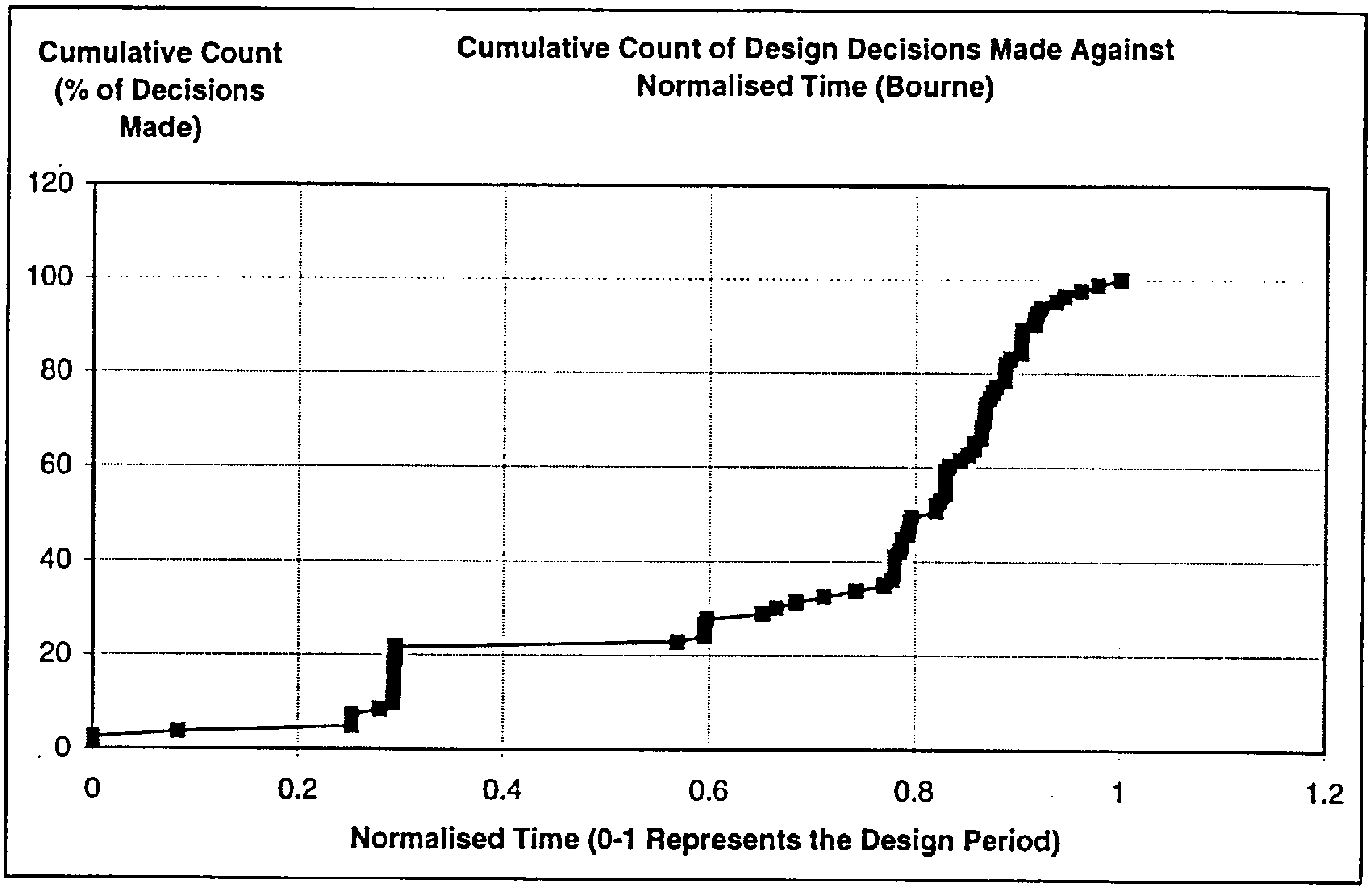


Figure I.1 - Cumulative Count of Design Decisions Made Against Normalised Time (Bourne)

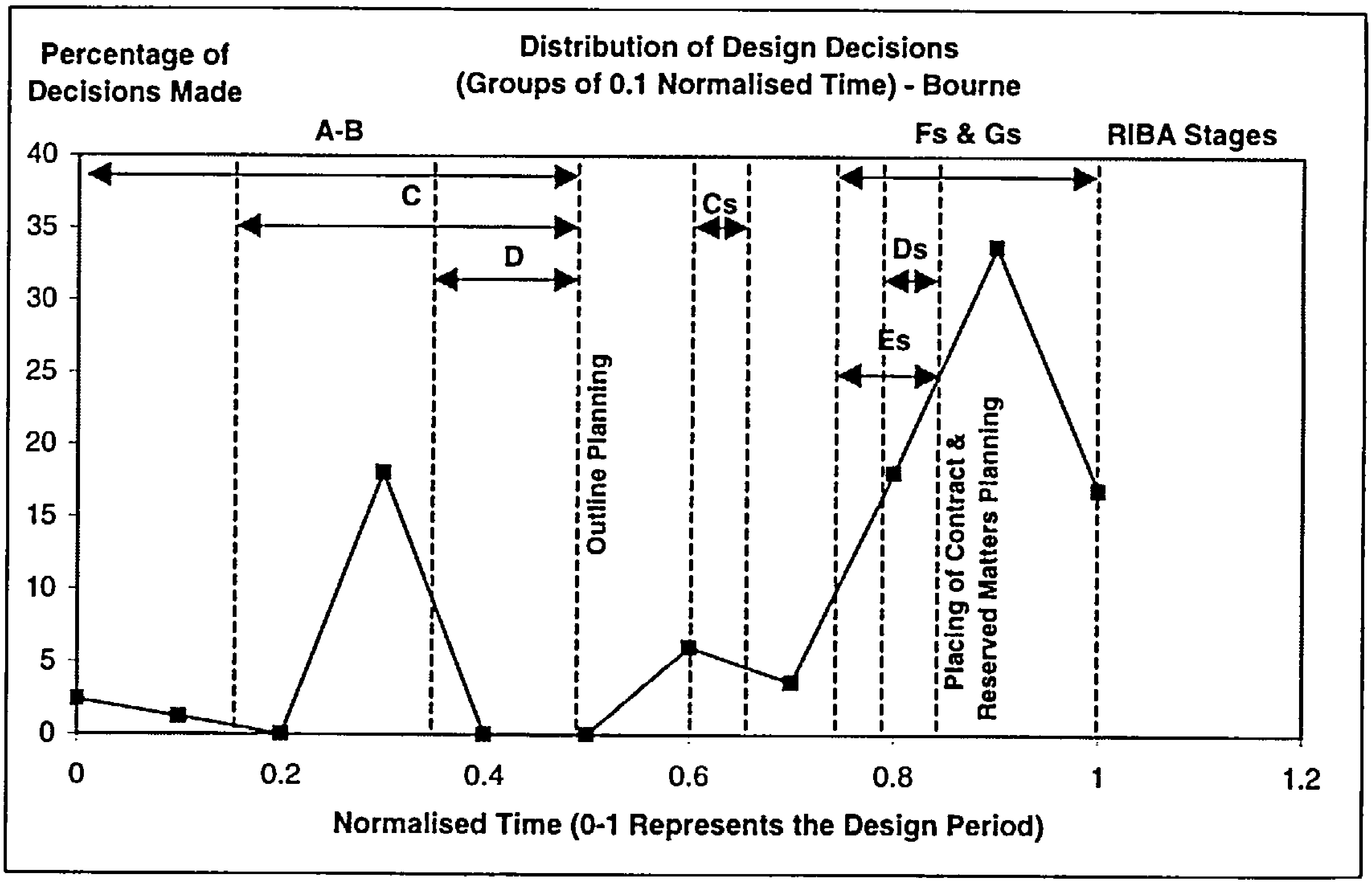


Figure I.2 - Distribution of Design Decisions (Groups of 0.1 Normalised Time) – Bourne

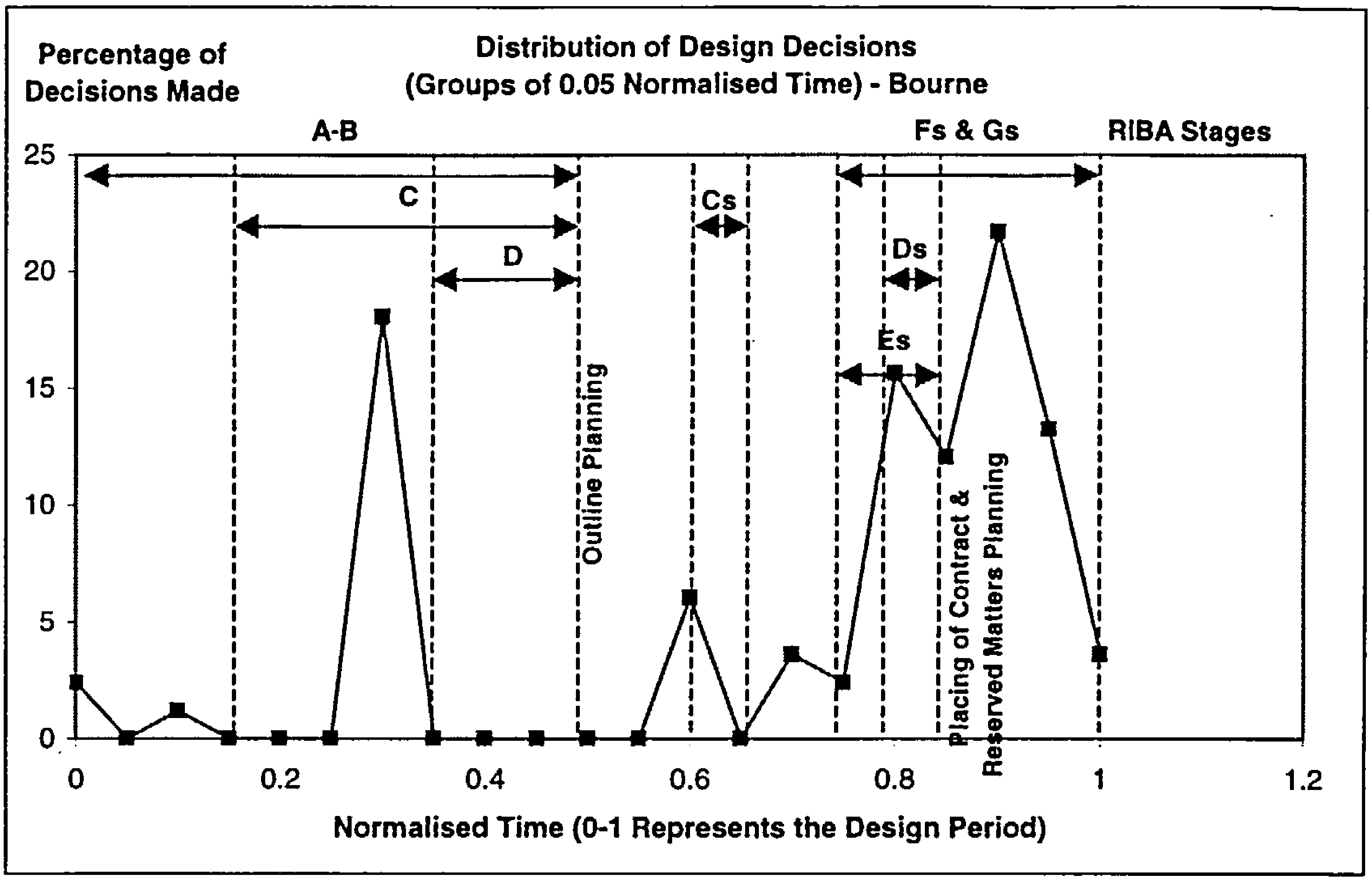


Figure I.3 - Distribution of Design Decisions (Groups of 0.05 Normalised Time) – Bourne

Bourne Design Team Discipline	Company
Acoustic Engineer	Lee Cunningham Partnership
Architect	Stanley Bragg Partnership
Architect (Fit Out)	Hadfield Cawkwell Davidson
Civil Engineer	White Young Green
Client	J Sainsbury
Client's Agent (QS)	Henry Riley & Son
Contractor (Project Manager)	RG Carter
Contractor's QS	BDB
Developer	Carter Commercial
Developers Agent (QS)	Dickson Powell
Highways Engineer	Flynn and Rothwell
Legal Advisor	McGuinness Finch
Party Wall Surveyor	GL Hearn
Planning Adviser to Sainsbury	Town Planning Consultants
Planning Officer	South Kesteven District Council
Public Relations for Client	Greylink
Refrigeration	Oaksmere
Services Engineer	Roberts & Partners
Steel Sub Contractor	TSI
Structural Engineer	White Young Green

Table I.2 – Design Team (Chelmsford)

Decision Maker	Decision Number	Decision Order	Bourne Design Decision Made	Normalised Time
Architect	9	1	Extent of demolition on site - buildings at ground level	0
Architect	2	4	Structural bay / grid dimensions	0.252683732
Architect	5	5	Footprint of initial building design	0.252683732
Architect	1	6	Selection of the frame system / material	0.252683732
Architect	65	8	Landscaping approach (decision for 30k budget)	0.292320396
Architect	70	20	Specifying the amount of glazing required	0.596201486
Architect	71	23	Customer & staff car parking location	0.597853014
Architect	3	27	Configuration / Layout of the structure	0.711808423
Architect	25	30	Decision to have an acoustic screen around exposed plant	0.777869529
Architect	80	35	Rendered panel in external skin	0.787778695
Architect	20	41	Decided to include a pedestrian walkway canopy	0.820809249
Architect	26	43	Arrangement of external skin - depth of wall (size of cavity)	0.824938068
Architect	27	44	Selection of Insulation type	0.829066887
Architect	7	52	Specification of the building footprint / configuration	0.857142857
Architect	76	54	Paving material selection	0.863748968
Architect	55	55	Selection of car parking lighting system	0.863748968
Architect	28	57	External skin - architectural features	0.867052023
Architect	29	58	Selection of material for external skin	0.867052023
Architect	54	76	Car park drainage system	0.918249381
Architect	37	77	Specification of means of escape doors	0.921552436
Architect	38	78	Specification of service doors	0.937241949
Architect	69	80	Selection of the type of windows / glazing	0.9611891
Architect	39	81	Specification of service yard gate	0.977704377
Architect	84	82	Enclosure type for substation	1
Client - Sainsbury	82	19	Position of service bays	0.569777044
Client - Sainsbury	63	21	CCTV (internally only)	0.596201486
Client - Sainsbury	64	22	Telecommunications specification (telephones, computer lines, Granada satellite system)	0.596201486
Client - Sainsbury	74	31	Location of plant room	0.780346821
Client - Sainsbury	36	36	The organisation of internal space	0.787778695
Client - Sainsbury	75	37	Decision to have open / closed plant	0.792733278
Client - Sainsbury	66	38	Location of service yard	0.794384806
Client - Sainsbury	58	39	Location of the lift system	0.79521057
Client - Sainsbury	13	50	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure	0.843930636
Client - Sainsbury	6	53	Final footprint for building design	0.857142857
Client - Sainsbury	59	56	External signage configuration	0.864574732
Client - Sainsbury	17	59	To include wind catchers in the roof system	0.867877787
Client - Sainsbury	68	74	The decision to include recycling facilities on the service road - i.e. to service yard	0.915772089
Contractor	31	26	Selection floor finish (concrete floor finish - not final finish)	0.684558216
Contractor	22	42	Selection of the roof system / material for the plant room	0.820809249

Contractor	**81**	49	Selection of insulation material for the roof	0.833195706
Contractor	**83**	51	Dimension between external skin and gridline	0.85136251
Contractor	**8**	62	Cut and fill exercise required to level off the site (store level on site)	0.875309661
Contractor	**49**	73	Selection of roof drainage system	0.904211396
Developer	**10**	2	Extent of the ground level demolition	0
Developer	**72**	7	Customer & staff car parking surface material selection	0.279933939
Developer	**57**	9	Selection of lift system for loading bay	0.292320396
Developer	**18**	10	Selection of the roof system / material	0.29314616
Developer	**24**	11	Selection of internal skin material	0.29314616
Developer	**16**	12	Arrangement of the roof structure	0.29314616
Developer	**15**	13	Selection of the roof structure type	0.29314616
Developer	**19**	14	Arrangement of the roof system / profile	0.29314616
Developer	**23**	15	Selection of external skin system / material	0.29314616
Developer	**34**	16	Type of fire compartmentation to be used (partition wall - between sales and domestic)	0.294797688
Developer	**33**	17	Type of internal partition wall used (to define areas of space for different uses)	0.294797688
Developer's QS	**43**	83	Capacity of the substation	1.082576383
Fitout Architect	**35**	40	Type of fire compartmentation to be used (partition wall - between sales and domestic)	0.796862097
Fitout Architect	**79**	60	Specification of internal doors	0.868703551
Fitout Architect	**32**	61	Selection of the final floor finish	0.87283237
Fitout Architect	**62**	64	Escape routes defined	0.886870355
Fitout Architect	**60**	65	Fire protection for structural steel	0.886870355
Fitout Architect	**61**	66	Fire compartmentation	0.886870355
Fitout Architect	**78**	68	Specification of public access doors	0.892650702
Highways Engineer	**73**	3	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)	0.083402147
Services Engineer	**77**	28	Positioning the service meter cupboard	0.743187448
Services Engineer	**41**	32	Configuration of ventilation system	0.780346821
Services Engineer	**42**	33	Location of the substation	0.780346821
Services Engineer	**40**	34	Type of ventilation system selected	0.780346821
Services Engineer	**46**	45	Gas capacity	0.829066887
Services Engineer	**47**	46	Routing of Water supply (decided to route with other services)	0.829066887
Services Engineer	**48**	47	Water capacity	0.829066887
Services Engineer	**45**	48	Routing of Gas supply (decided to route with other services)	0.829066887
Services Engineer	**44**	67	Routing of electrical services	0.887696119

Services Engineer	**56**	79	Selection of store perimeter lighting	0.944673823
Structural Engineer	**67**	18	Surface finish of service yard	0.294797688
Structural Engineer	**12**	24	Selection of substructure system / material	0.652353427
Structural Engineer	**30**	25	Selection of the floor system / configuration	0.665565648
Structural Engineer	**11**	29	Extent of the below ground level demolition	0.770437655
Structural Engineer	**4**	63	Bracing to steel frame (amount and arrangement)	0.878612717
Structural Engineer	**52**	69	Routing of soiled water drain (roof and landscape water run off)	0.903385632
Structural Engineer	**53**	70	Capacity of soiled water drain (roof and landscape water run off)	0.903385632
Structural Engineer	**51**	71	Capacity of foul water drain	0.903385632
Structural Engineer	**50**	72	Routing of foul water drain	0.903385632
Structural Engineer	**14**	75	Decision to incorporate a gas permeable membrane into the substructure	0.916597853

Table I.4 – List of System / Sub-System Level Design Decisions for the Bourne Case Study by Order of Decision Maker

Decision Number	Bourne Decisions That The Architect Was Involved In Making
4	Bracing to steel frame (amount and arrangement)
5	Footprint of initial building design
6	Final footprint for building design
8	Cut and fill exercise required to level off the site (store level on site)
10	Extent of the ground level demolition
15	Selection of the roof structure type
16	Arrangement of the roof structure
18	Selection of the roof system / material
19	Arrangement of the roof system / profile
20	Decided to include a pedestrian walkway canopy
22	Selection of the roof system / material for the plant room
23	Selection of external skin system / material
24	Selection of internal skin material
25	Decision to have an acoustic screen around exposed plant
26	Arrangement of external skin - depth of wall (size of cavity)
27	Selection of Insulation type
28	External skin - architectural features
29	Selection of material for external skin
33	Type of internal partition wall used (to define areas of space for different uses)
34	Type of fire compartmentation to be used (partition wall - between sales and domestic)
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
37	Specification of means of escape doors
38	Specification of service doors
39	Specification of service yard gate
40	Type of ventilation system selected
41	Configuration of ventilation system
42	Location of the substation
49	Selection of roof drainage system
54	Car park drainage system
55	Selection of car parking lighting system
56	Selection of store perimeter lighting
57	Selection of lift system for loading bay
58	Location of the lift system
62	Escape routes defined
65	Landscaping approach (decision for 30k budget)
66	Location of service yard
67	Surface finish of service yard
68	The decision to include recycling facilities on the service road - i.e. to service yard
69	Selection of the type of windows / glazing
70	Specifying the amount of glazing required
71	Customer & staff car parking location
72	Customer & staff car parking surface material selection
73	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)
74	Location of plant room
75	Decision to have open / closed plant
76	Paving material selection
78	Specification of public access doors
79	Specification of internal doors
80	Rendered panel in external skin
81	Selection of insulation material for the roof

82	Position of service bays
83	Dimension between external skin and gridline
84	Enclosure type for substation

Table I.5 - List of System / Sub-System Level Design Decisions that the Architect was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Developer Was Involved In Making
1	Selection of the frame system / material
2	Structural bay / grid dimensions
5	Footprint of initial building design
6	Final footprint for building design
12	Selection of substructure system / material
13	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure
15	Selection of the roof structure type
16	Arrangement of the roof structure
17	To include wind catchers in the roof system
18	Selection of the roof system / material
19	Arrangement of the roof system / profile
22	Selection of the roof system / material for the plant room
23	Selection of external skin system / material
24	Selection of internal skin material
32	Selection of the final floor finish
33	Type of internal partition wall used (to define areas of space for different uses)
34	Type of fire compartmentation to be used (partition wall - between sales and domestic)
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
57	Selection of lift system for loading bay
67	Surface finish of service yard
72	Customer & staff car parking surface material selection
73	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)
74	Location of plant room
75	Decision to have open / closed plant
76	Paving material selection
77	Positioning the service meter cupboard
80	Rendered panel in external skin

Table I.6 - List of System / Sub-System Level Design Decisions that the Developer was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Developer's Agent Was Involved In Making
3	Configuration / Layout of the structure
13	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure
18	Selection of the roof system / material
20	Decided to include a pedestrian walkway canopy
22	Selection of the roof system / material for the plant room
23	Selection of external skin system / material
24	Selection of internal skin material
33	Type of internal partition wall used (to define areas of space for different uses)
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
43	Capacity of the substation
65	Landscaping approach (decision for 30k budget)
74	Location of plant room
75	Decision to have open / closed plant
76	Paving material selection
80	Rendered panel in external skin

Table I.7 - List of System / Sub-System Level Design Decisions that the Developer's Agent was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The End User Was Involved In Making
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
36	The organisation of internal space
37	Specification of means of escape doors
38	Specification of service doors
39	Specification of service yard gate
40	Type of ventilation system selected
41	Configuration of ventilation system
42	Location of the substation
43	Capacity of the substation
58	Location of the lift system
59	External signage configuration
60	Fire protection for structural steel
61	Fire compartmentation
63	CCTV (internally only)
64	Telecommunications specification (telephones, computer lines, Granada satellite system)
66	Location of service yard
68	The decision to include recycling facilities on the service road - i.e. to service yard
71	Customer & staff car parking location
74	Location of plant room
75	Decision to have open / closed plant
76	Paving material selection
78	Specification of public access doors
79	Specification of internal doors
82	Position of service bays
84	Enclosure type for substation

Table I.8 - List of System / Sub-System Level Design Decisions that the End User was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Highways Engineer Was Involved In Making
5	Footprint of initial building design
10	Extent of the ground level demolition
73	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)

Table I.9 - List of System / Sub-System Level Design Decisions that the Highways Engineer was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Landscape Architect Was Involved In Making
65	Landscaping approach (decision for 30k budget)

Table I.10 - List of System / Sub-System Level Design Decisions that the Landscape Architect was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Legal Consultant Was Involved In Making
5	Footprint of initial building design
10	Extent of the ground level demolition

Table I.11 - List of System / Sub-System Level Design Decisions that the Legal Consultant was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Planning Authority Was Involved In Making
5	Footprint of initial building design
6	Final footprint for building design
7	Specification of the building footprint / configuration
20	Decided to include a pedestrian walkway canopy
26	Arrangement of external skin - depth of wall (size of cavity)
28	External skin - architectural features
29	Selection of material for external skin
74	Location of plant room
75	Decision to have open / closed plant
80	Rendered panel in external skin

Table I.12 - List of System / Sub-System Level Design Decisions that the Planning Authority was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Planning Supervisor Was Involved In Making
5	Footprint of initial building design
10	Extent of the ground level demolition

Table I.13 - List of System / Sub-System Level Design Decisions that the Planning Supervisor was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Project Manager Was Involved In Making
3	Configuration / Layout of the structure
22	Selection of the roof system / material for the plant room
25	Decision to have an acoustic screen around exposed plant
26	Arrangement of external skin - depth of wall (size of cavity)
27	Selection of insulation type
29	Selection of material for external skin
31	Selection floor finish (concrete floor finish - not final finish)
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
43	Capacity of the substation
49	Selection of roof drainage system
54	Car park drainage system
60	Fire protection for structural steel
61	Fire compartmentation
65	Landscaping approach (decision for 30k budget)
66	Location of service yard
68	The decision to include recycling facilities on the service road - i.e. to service yard
69	Selection of the type of windows / glazing
70	Specifying the amount of glazing required
71	Customer & staff car parking location
74	Location of plant room
75	Decision to have open / closed plant
76	Paving material selection
77	Positioning the service meter cupboard
80	Rendered panel in external skin
81	Selection of insulation material for the roof
82	Position of service bays
83	Dimension between external skin and gridline
84	Enclosure type for substation

Table I.14 - List of System / Sub-System Level Design Decisions that the Project Manager was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Quantity Surveyor Was Involved In Making
1	Selection of the frame system / material
2	Structural bay / grid dimensions
6	Final footprint for building design
10	Extent of the ground level demolition
12	Selection of substructure system / material
17	To include wind catchers in the roof system
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
37	Specification of means of escape doors
38	Specification of service doors
39	Specification of service yard gate
40	Type of ventilation system selected
41	Configuration of ventilation system
42	Location of the substation
43	Capacity of the substation
63	CCTV (internally only)
64	Telecommunications specification (telephones, computer lines, Granada satellite system)
68	The decision to include recycling facilities on the service road - i.e. to service yard
69	Selection of the type of windows / glazing
70	Specifying the amount of glazing required
71	Customer & staff car parking location
74	Location of plant room
75	Decision to have open / closed plant
82	Position of service bays
84	Enclosure type for substation

Table I.15 - List of System / Sub-System Level Design Decisions that the Quantity Surveyor was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Services Engineer Was Involved In Making
7	Specification of the building footprint / configuration
13	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure
17	To include wind catchers in the roof system
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
36	The organisation of internal space
40	Type of ventilation system selected
41	Configuration of ventilation system
42	Location of the substation
43	Capacity of the substation
44	Routing of electrical services
45	Routing of gas supply (decided to route with other services)
46	gas capacity
47	Routing of water supply (decided to route with other services)
48	Water capacity
50	Routing of foul water drain
51	Capacity of foul water drain
52	Routing of soiled water drain (roof and landscape water run off)
53	Capacity of soiled water drain (roof and landscape water run off)
55	Selection of car parking lighting system
56	Selection of store perimeter lighting

69	Selection of the type of windows / glazing
70	Specifying the amount of glazing required
74	Location of plant room
75	Decision to have open / closed plant
77	Positioning the service meter cupboard
78	Specification of public access doors
79	Specification of internal doors
82	Position of service bays
84	Enclosure type for substation

Table I.16 - List of System / Sub-System Level Design Decisions that the Services Engineer was Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Specialist Consultants Was Involved In Making	Specialist Consultants
4	Bracing to steel frame (amount and arrangement)	Store planner for Sainsbuy's, Fitout Architect
7	Specification of the building footprint / configuration	Fitout architect
12	Selection of substructure system / material	To advise the structural engineer on which foundat
32	Selection of the final floor finish	Fitout architect
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)	Fitout architect
36	The organisation of internal space	Fitout architect,
37	Specification of means of escape doors	Fitout architect,
38	Specification of service doors	Fitout architect,
39	Specification of service yard gate	Fitout architect,
44	Routing of electrical services	Non-statutory undertaker
55	Selection of car parking lighting system	Holophane
56	Selection of store perimeter lighting	Lighting supplier
58	Location of the lift system	Fitout architect
59	External signage configuration	Fitout architect
60	Fire protection for structural steel	Fitout architect
61	Fire compartmentation	Fitout architect
62	Escape routes defined	Fitout architect and fire officer
63	CCTV (internally only)	Fitout architect
64	Telecommunications specification (telephones, computer lines, Granada satellite system)	Fitout architect
66	Location of service yard	Fitout architect
68	The decision to include recycling facilities on the service road - i.e. to service yard	Fitout architect
69	Selection of the type of windows / glazing	Fitout architect
70	Specifying the amount of glazing required	Fitout architect, windows and doors subcontractor
71	Customer & Staff car parking location	Fitout architect
74	Location of plant room	Fitout architect
75	Decision to have open / closed plant	Fitout architect
76	Paving material selection	Fitout architect
78	Specification of public access doors	Fitout architect
79	Specification of internal doors	Fitout architect
82	Position of service bays	Fitout architect

Table I.17 - List of System / Sub-System Level Design Decisions that Specialist Consultants were Involved in Making (Bourne)

Decision Number	Bourne Decisions That The Structural Engineer Was Involved In Making
2	Structural bay / grid dimensions
3	Configuration / Layout of the structure
6	Final footprint for building design
7	Specification of the building footprint / configuration
13	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure
14	Decision to incorporate a gas permeable membrane into the substructure
22	Selection of the roof system / material for the plant room
26	Arrangement of external skin - depth of wall (size of cavity)
30	Selection of the floor system / configuration
31	Selection floor finish (concrete floor finish - not final finish)
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)
40	Type of ventilation system selected
41	Configuration of ventilation system
42	Location of the substation
44	Routing of electrical services
45	Routing of gas supply (decided to route with other services)
46	gas capacity
47	Routing of water supply (decided to route with other services)
48	Water capacity
50	Routing of foul water drain
51	Capacity of foul water drain
52	Routing of soiled water drain (roof and landscape water run off)
53	Capacity of soiled water drain (roof and landscape water run off)
54	Car park drainage system
68	The decision to include recycling facilities on the service road - i.e. to service yard
74	Location of plant room
75	Decision to have open / closed plant
77	Positioning the service meter cupboard
82	Position of service bays
83	Dimension between external skin and gridline
84	Enclosure type for substation

Table I.18 - List of System / Sub-System Level Design Decisions that the Structural Engineer was Involved in Making (Bourne)

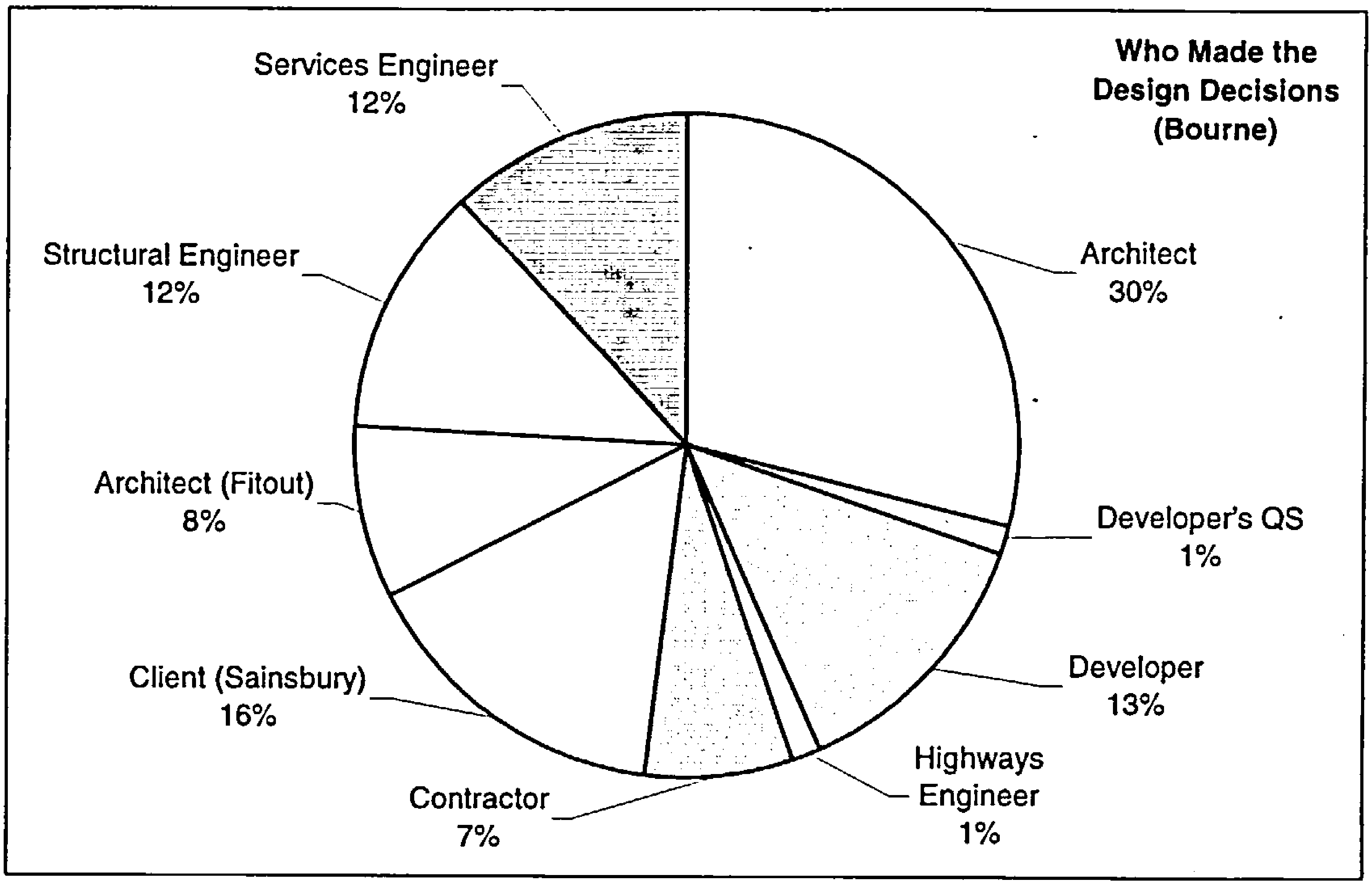


Figure I.4 – Who Made the Design Decisions (Bourne)

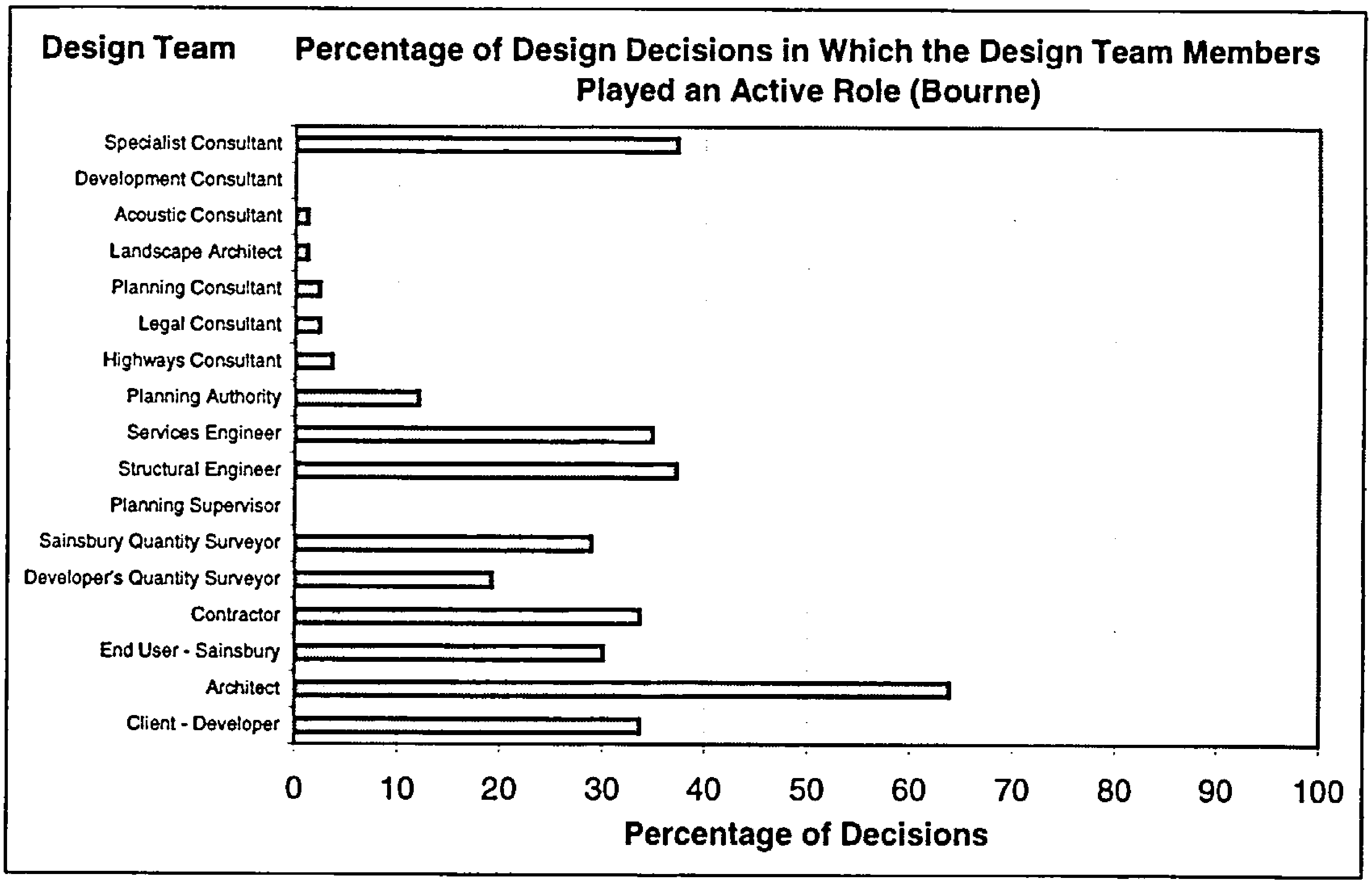


Figure I.5 – Percentage of Design Decisions in Which the Design Team Members Played an Active Role (Bourne)

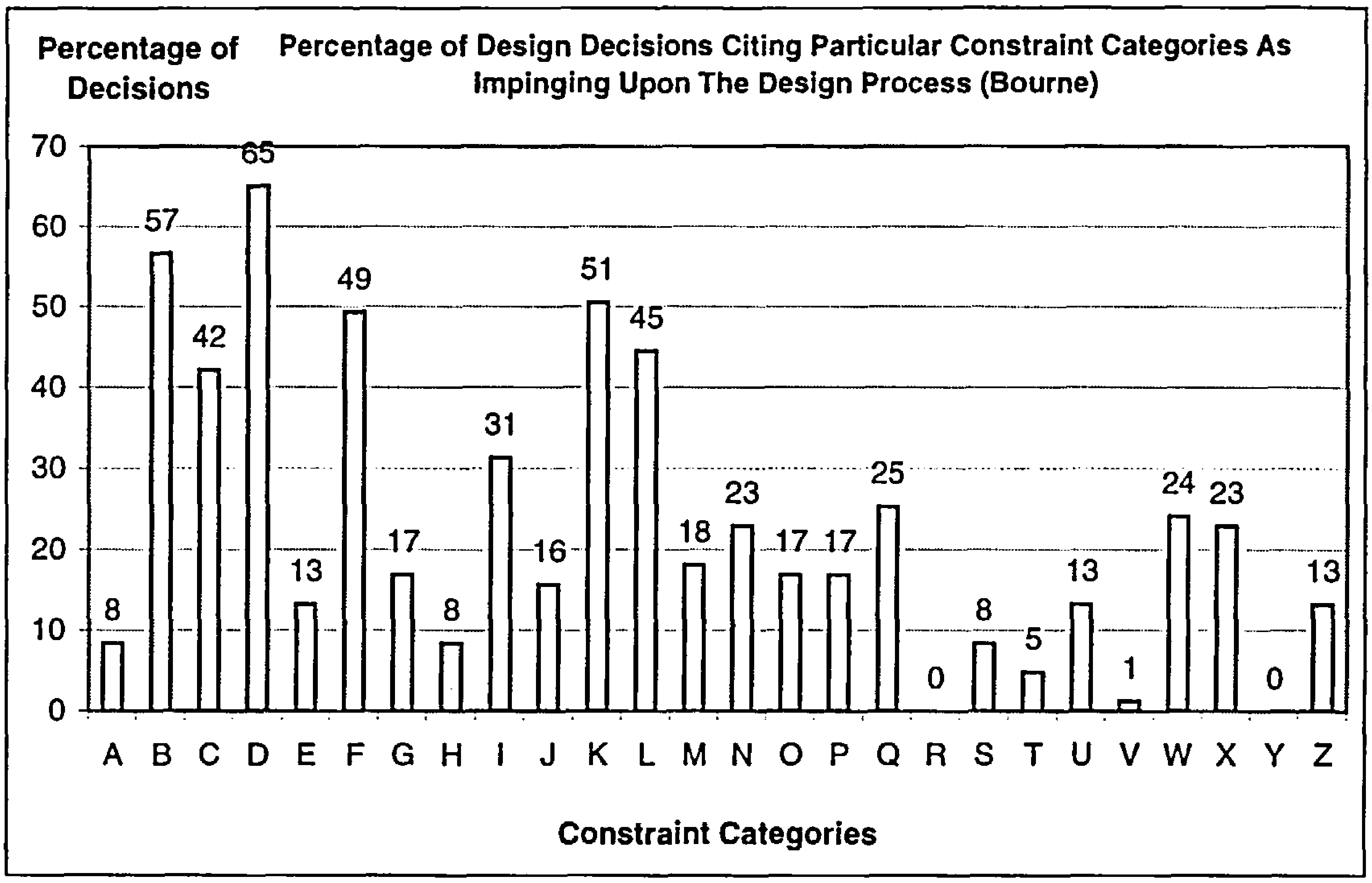


Figure I.6 – Percentage of Design Decisions Particular Constraint Categories are Cited as Impinging Upon the Design Process (Bourne)

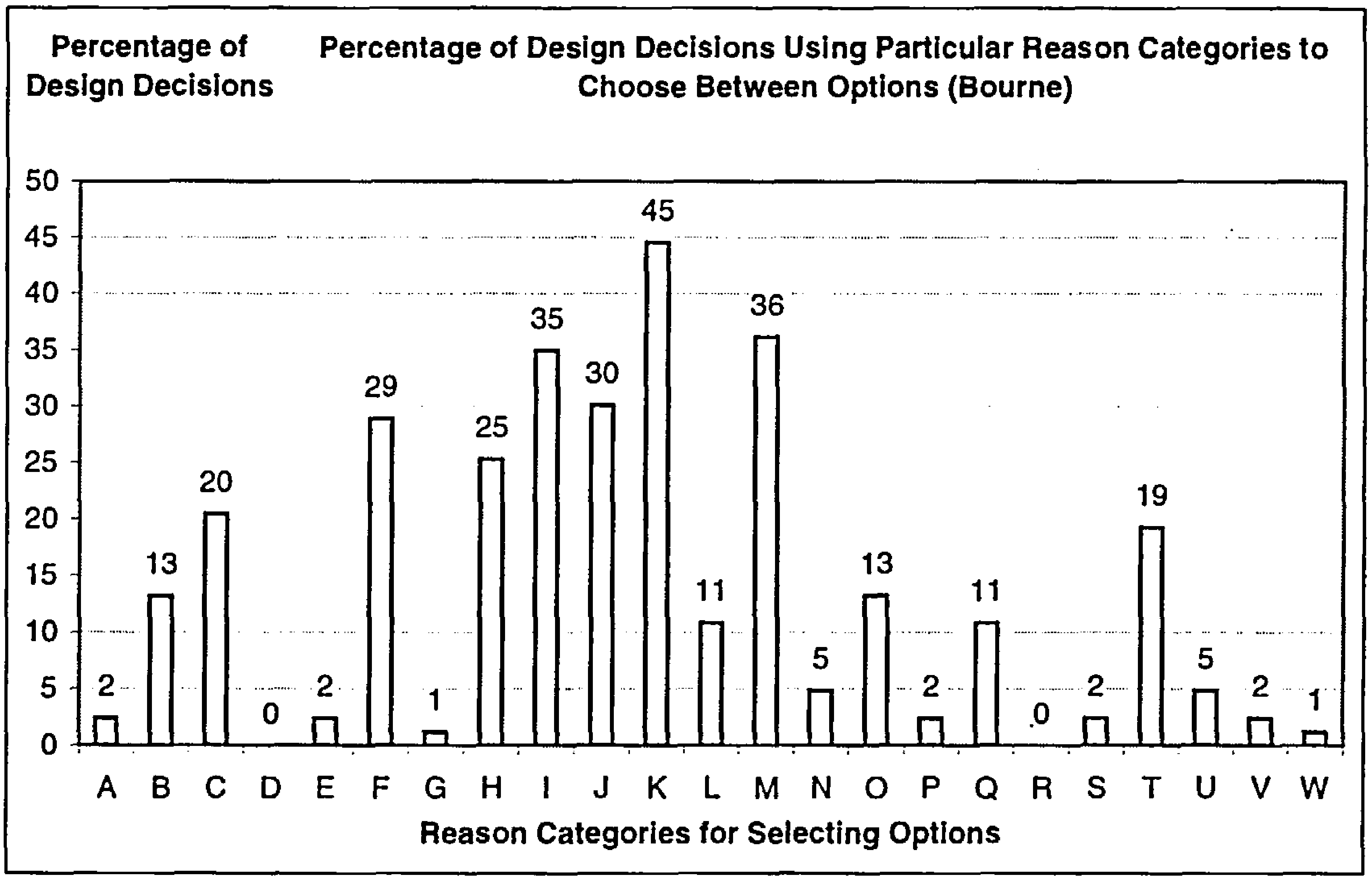


Figure I.7 – Percentage of Design Decisions Using Particular Reason Categories to Choose Between Options (Bourne)

Decision Number	Bourne Decision Made	Constraints Impinging Design - Categories Cited	Reason For Selecting Options - Categories Cited
1	Selection of the frame system / material	A,D,E,H,I,K,O,U	H,I,O,T,U
2	Structural bay / grid dimensions	B,C,D,E,I,J,M,Q	H,I,J,K,T
3	Configuration / Layout of the structure	A,B,C,D,F,I,J,K,L, Q,X	B,J,K
4	Bracing to steel frame (amount and arrangement)	B,D,F,U,X	F,K,M
5	Footprint of initial building design	B,D,F,K,L,M,U,T,X	K,Q,T
6	Final footprint for building design	B,D,F,K,L,M,U,T,X	A,B,F,M
7	Specification of the building footprint / configuration	B,D,F,K,L,T,X	B,C,J,M,O
8	Cut and fill exercise required to level off the site (store level on site)	D,E,F,I,J,N,O,W	H,I,O
9	Extent of demolition on site - buildings at ground level	B,D,M,N,O,T,W,Z	F,I,K,M,S
10	Extent of the ground level demolition	D,L,N,T,W,Z	F,I,K,M,S
11	Extent of the below ground level demolition	D,L,N,T,W,Z	M,N,U
12	Selection of substructure system / material	D,I,K,O	B,H,I,K,O
13	To allow for duct runs, refrigeration pipes and power supply to checkout within the arrangement of the substructure	A,B,E,F,I,N,Q,U	I
14	Decision to incorporate a gas permeable membrane into the substructure	D,J,K,N,W	J
15	Selection of the roof structure type	F,I,J,M,O,U	I,J,T
16	Arrangement of the roof structure	D,E,F,I	H,I,J,K
17	To include wind catchers in the roof system	D,F,I,K,L,Q,W	I,K
18	Selection of the roof system / material	E,F,H,I,L,M,O,Q	F,I,J,T
19	Arrangement of the roof system / profile	D,F,I,K,N,P,X	F,H,I,J,Q
20	Decided to include a pedestrian walkway canopy	D,K,L,Q	K,Q
22	Selection of the roof system / material for the plant room	A,E,F,H,I,J,O	F,H,I,J,Q
23	Selection of external skin system / material	F,I,L,M,Q,W,X	I,K,J,Q,T
24	Selection of internal skin material	I,K,L,O	I,J,K,T
25	Decision to have an acoustic screen around exposed plant	D,I,K,Q,W	F,H,K,L,O,Q
26	Arrangement of external skin - depth of wall (size of cavity)	D,K,L,O,Q	F,H,O
27	Selection of Insulation type	D,F,H,L	H,I,K
28	External skin - architectural features	D,L,Q	L,Q
29	Selection of material for external skin	D,I,K,Q,U	I,L,Q
30	Selection of the floor system / configuration	A,D,H,J,K,O,U	H,K,M,O
31	Selection floor finish (concrete floor finish - not final finish)	D,H,O,V	H,K,O
32	Selection of the final floor finish	B,C,K,P	C,M
33	Type of internal partition wall (to define areas of space for different uses)	D,F,K,M,O,U,W	H,I,K,L,M,T
34	Type of fire compartmentation to be used (partition wall - between sales and domestic)	A,F,K,L,M,N,O	K,L,M,N
35	Type of fire compartmentation to be used (partition wall - between sales and domestic)	A,F,K,L,M,N,O	M
36	The organisation of internal space	B,C,G	C,E,M
37	Specification of means of escape doors	B,C,G,K,L,N,S	C,F,K,M
38	Specification of service doors	B,C,G,K	C,E,L,M
39	Specification of service yard gate	B,C,G,K,L,N,S	B,F,I,K,M
40	Type of ventilation system selected	B,C,D,F,G,I,J,L,P, W	B,F,I,K,M
41	Configuration of ventilation system	B,C,D,F,G,I,J,L,P, W	I,K
42	Location of the substation	D,F,P,S,X,Z	B,F,K
43	Capacity of the substation	B,S,U	G,O,T
44	Routing of electrical services	B,C,D,E,F,I	F,H,K

45	Routing of Gas supply (decided to route with other services)	B,D,F,X	H,U
46	Gas capacity	B,C,G,K	J,M,T
47	Routing of Water supply (decided to route with other services)	D,F	H,U
48	Water capacity	B,C,G,K	J,M,T
49	Selection of roof drainage system	D,I,K,P,Q	F
50	Routing of foul water drain	B,C,D,L,P	F,K
51	Capacity of foul water drain	B,C,G,L	F,J,M,T
52	Routing of soiled water drain (roof and landscape water run off)	B,C,D,L,P	F,K
53	Capacity of soiled water drain (roof and landscape water run off)	B,C,G,L	F,J,M,T
54	Car park drainage system	D,I,W	C,F,H,J
55	Selection of car parking lighting system	B,C,D,F,K,L,M	I,K
56	Selection of store perimeter lighting	B,C,D,K,M,Q	B,H,J,K
57	Selection of lift system for loading bay	B,C,D,F,G,M	C,M
58	Location of the lift system	B,C,D,E,F,G,K,X	C,M
59	External signage configuration	B,C	C,M
60	Fire protection for structural steel	D,F,K,L,N,X	B,J,K
61	Fire compartmentation	D,F,K,L,N,X	B,J,K
62	Escape routes defined	B,C,D,K,L,S,X	C,M
63	CCTV (internally only)	B,C,S,Z	M,V
64	Telecommunications specification (telephones, computer lines, Granada satellite system)	B,C,D,F,K	C,M
65	Landscaping approach (decision for 30k budget)	D,F,I,P,W	B,I,O
66	Location of service yard	B,C,D,F,K,L,Q,W, X,Z	C,F,K,L,N
67	Surface finish of service yard	B,C,D,F,I,K,M	H,J,K,O
68	The decision to include recycling facilities on the service road - ie to service yard	B,D,E,L,S,U,X	T
69	Selection of the type of windows / glazing	B,D,J,K,P,Q,W,Z	I,K
70	Specifying the amount of glazing required	B,D,J,K,P,Q,W,Z	C,I,M,N
71	Customer & Staff car parking location	B,D,F,X,Z	A,F,Q
72	Customer & Staff car parking surface material selection	B,D,F,I,J,K	J,M,W
73	Have two access points (1 service road entrance/exit, and 1 customer car parking entrance/exit)	D,L,N,X	F,K
74	Location of plant room	B,C,F,L,P,Q,W,Z	I
75	Decision to have open / closed plant	B,C,F,L,N,Q,W	F,I,K,L
76	Paving material selection	B,C,K,L,N,P	C,J,M
77	Positioning the service meter cupboard	D,F,K,P,X,Z	P,V
78	Specification of public access doors	B,C,I,L,Q,W	C,I,J,K
79	Specification of internal doors	B,C,K,N,Q,W	C,J,M
80	Rendered panel in external skin	D,F,L	L,Q
81	Selection of insulation material for the roof	K,L,M,N	I,T
82	Position of service bays	B,C,D,F,G	C,M
83	Dimension between external skin and gridline	D,E,H,I,J	H
84	Enclosure type for substation	B,C,D,F,G,K,N,Q, X	H,J,K,P

Table I.19 - List of System / Sub-System Level Design Decisions with Corresponding 'Constraint' and 'Reasons For Selection' Categories Cited (Bourne)

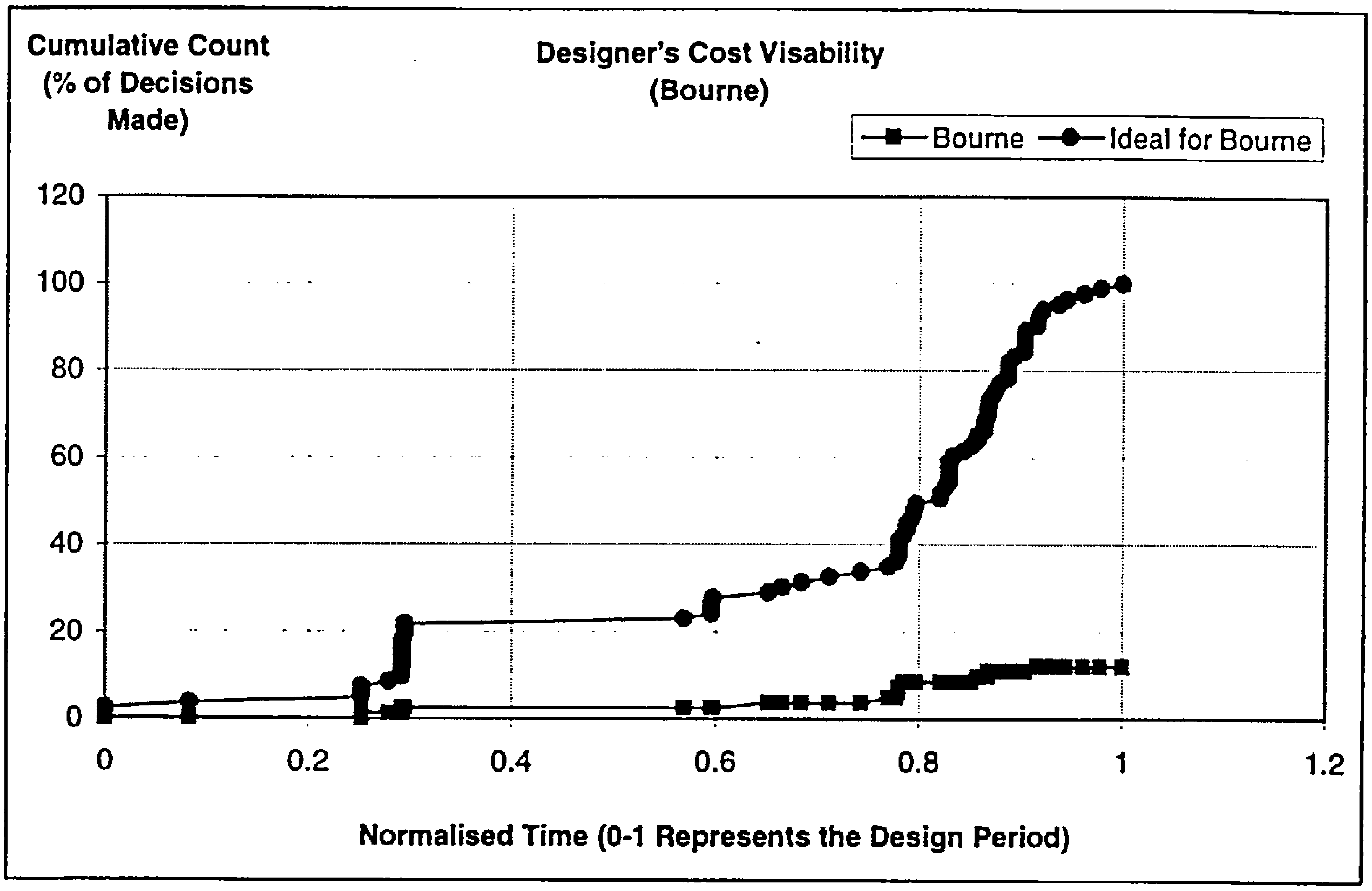


Figure I.8 – Designer's Cost Visibility (Bourne)

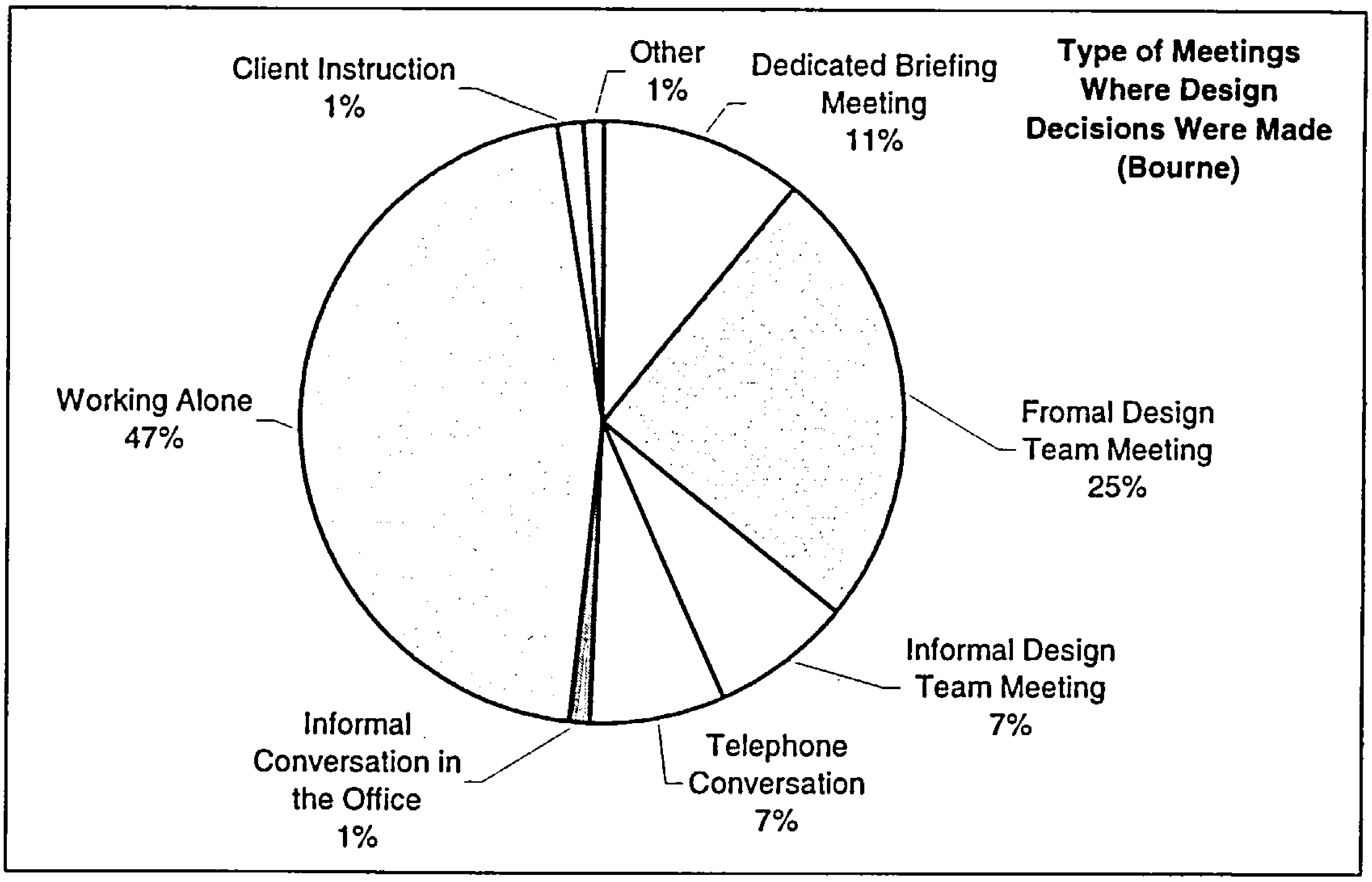


Figure I.9 – The Types of Meetings Where Design Decisions Were Made (Bourne)

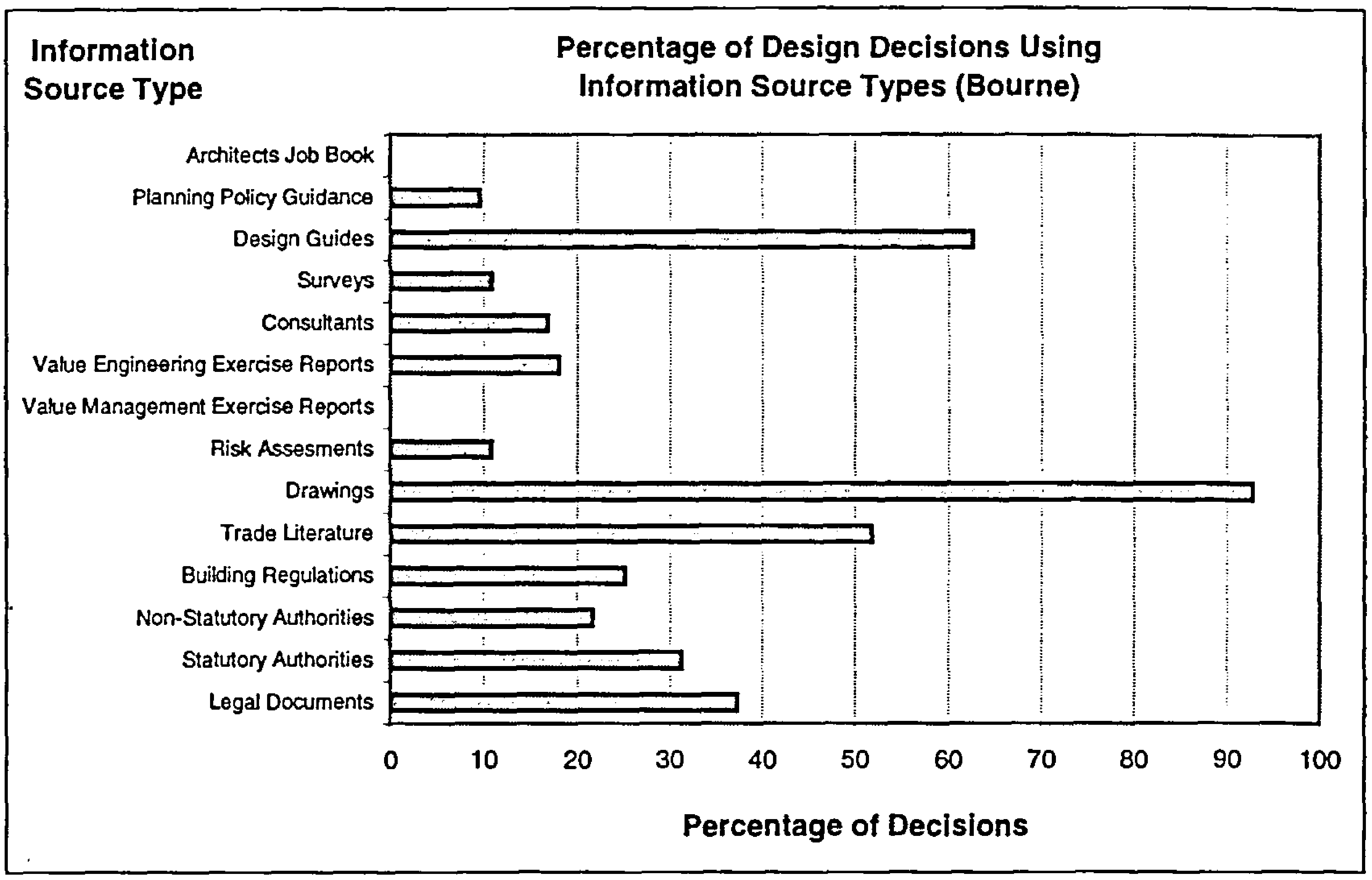


Figure I.10 – Percentage of Design Decisions Using Particular Information Source Types (Bourne)

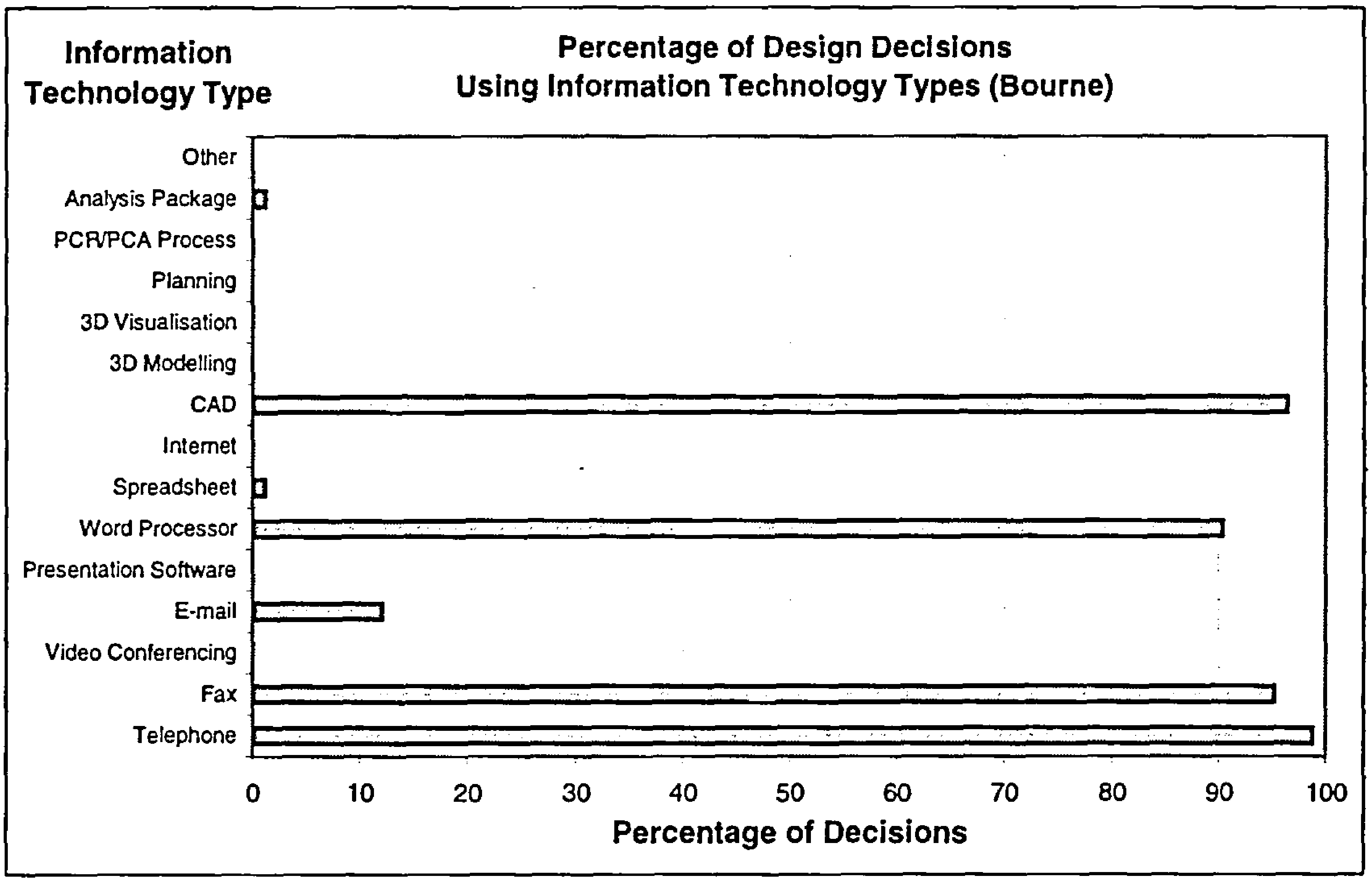


Figure I.11 – Percentage of Design Decisions Using Particular Information Technology Types (Bourne)

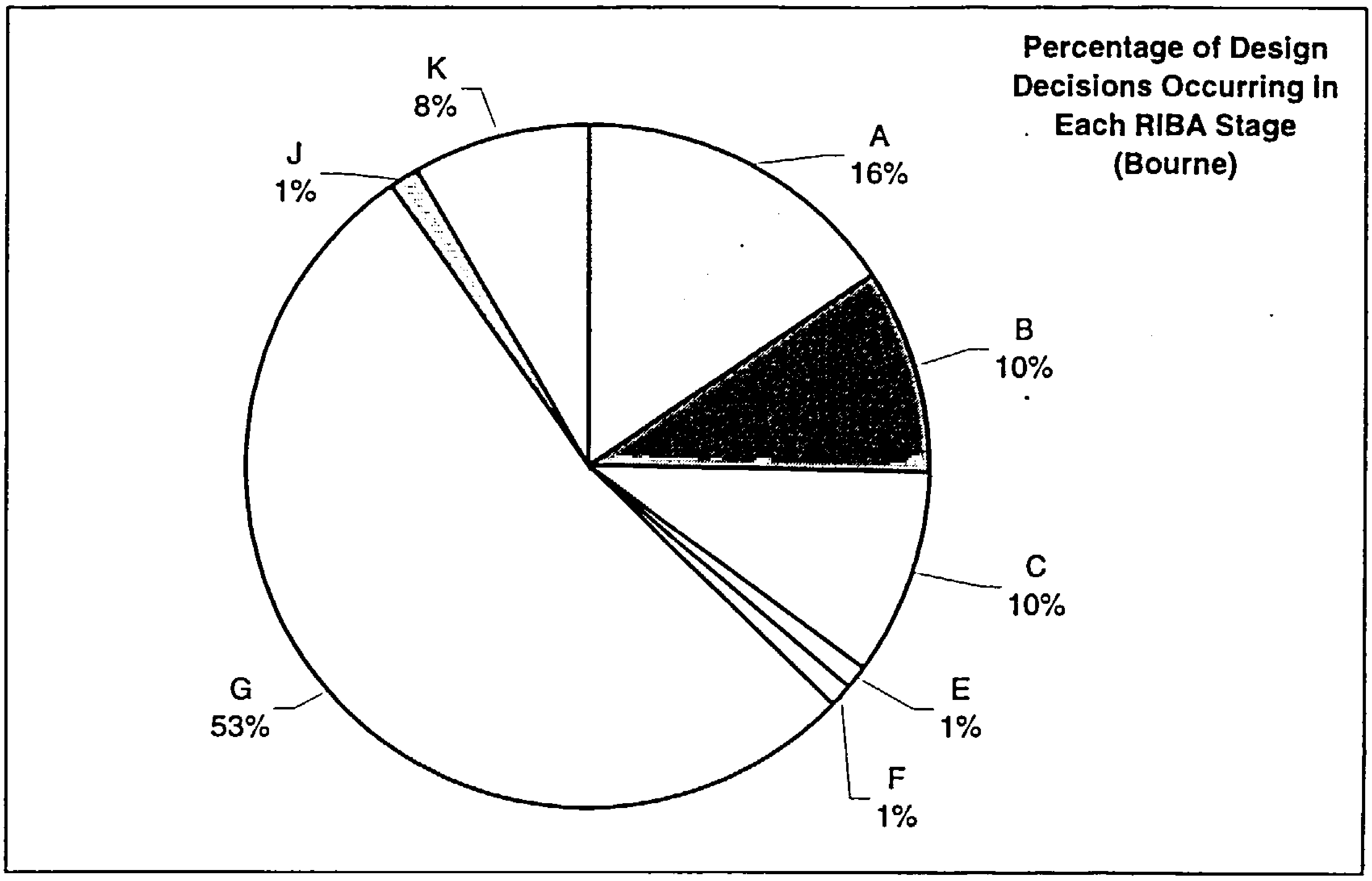


Figure I.12 – Percentage of Design Decisions Occurring in Each RIBA Stage (Bourne)

[BLANK PAGE]

APPENDIX J

List of Figures

Figure J.1 – Cumulative Count of Decisions Made Against Normalised Time (all three case studies) *2*
Figure J.2 – Gatwick & Chelmsford Design Decisions Made Against Normalised Time *3*
Figure J.3 – Chelmsford & Bourne Design Decisions Made Against Normalised Time *4*
Figure J.4 – Gatwick & Bourne Design Decisions Made Against Normalised Time *5*

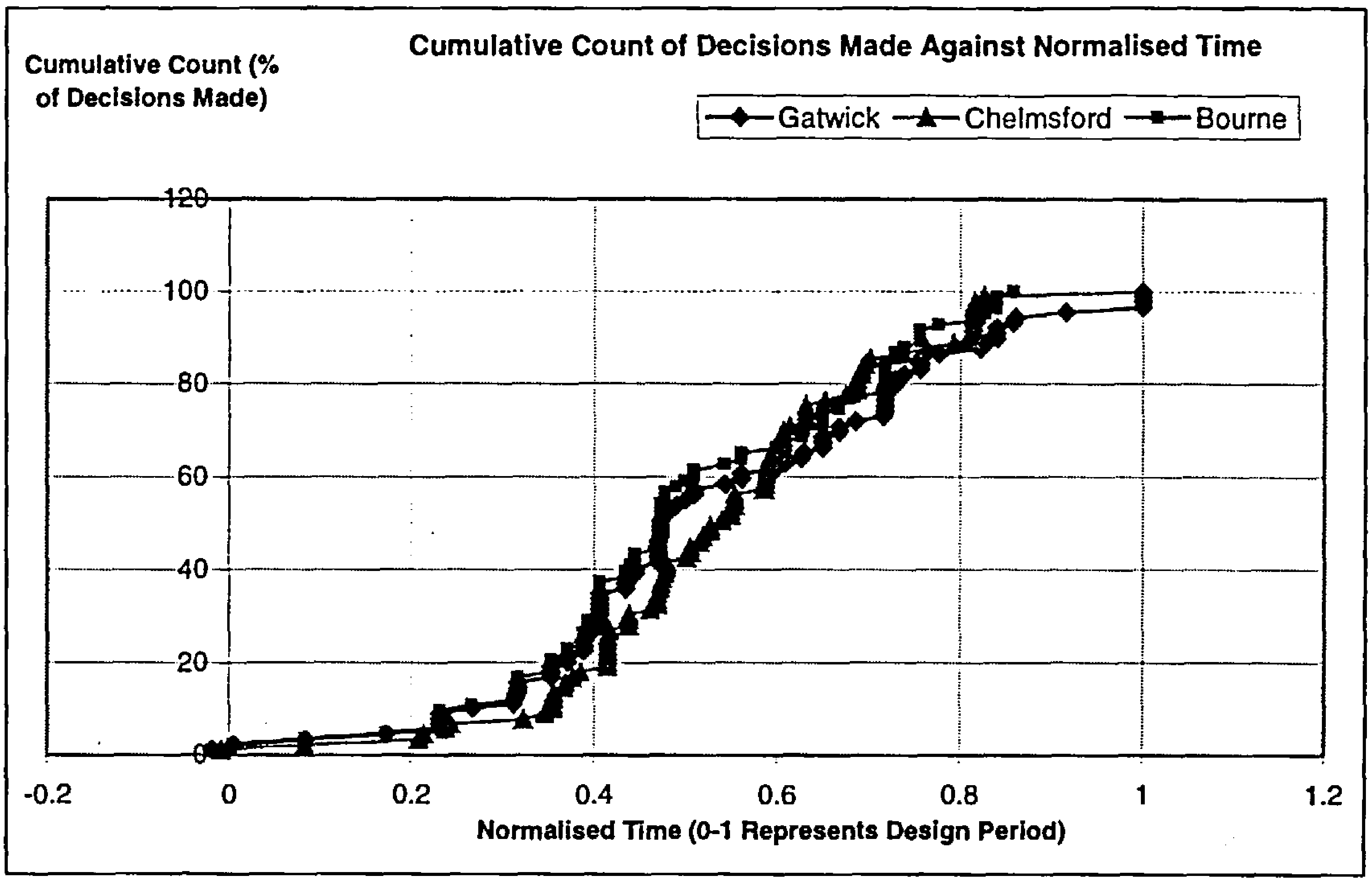


Figure J.1 – Cumulative Count of Decisions Made Against Normalised Time (all three case studies)

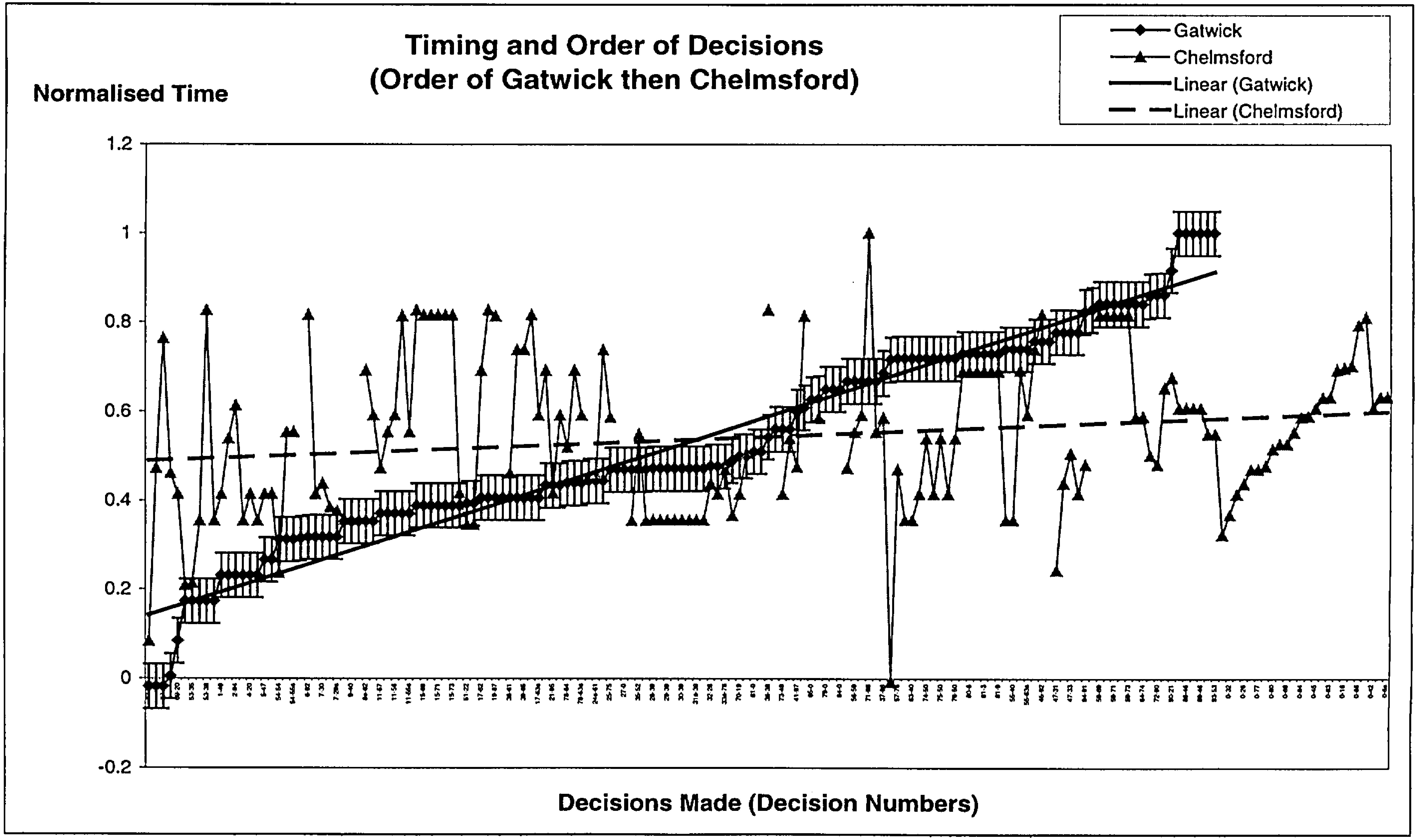


Figure J.2 – Gatwick & Chelmsford Design Decisions Made Against Normalised Time

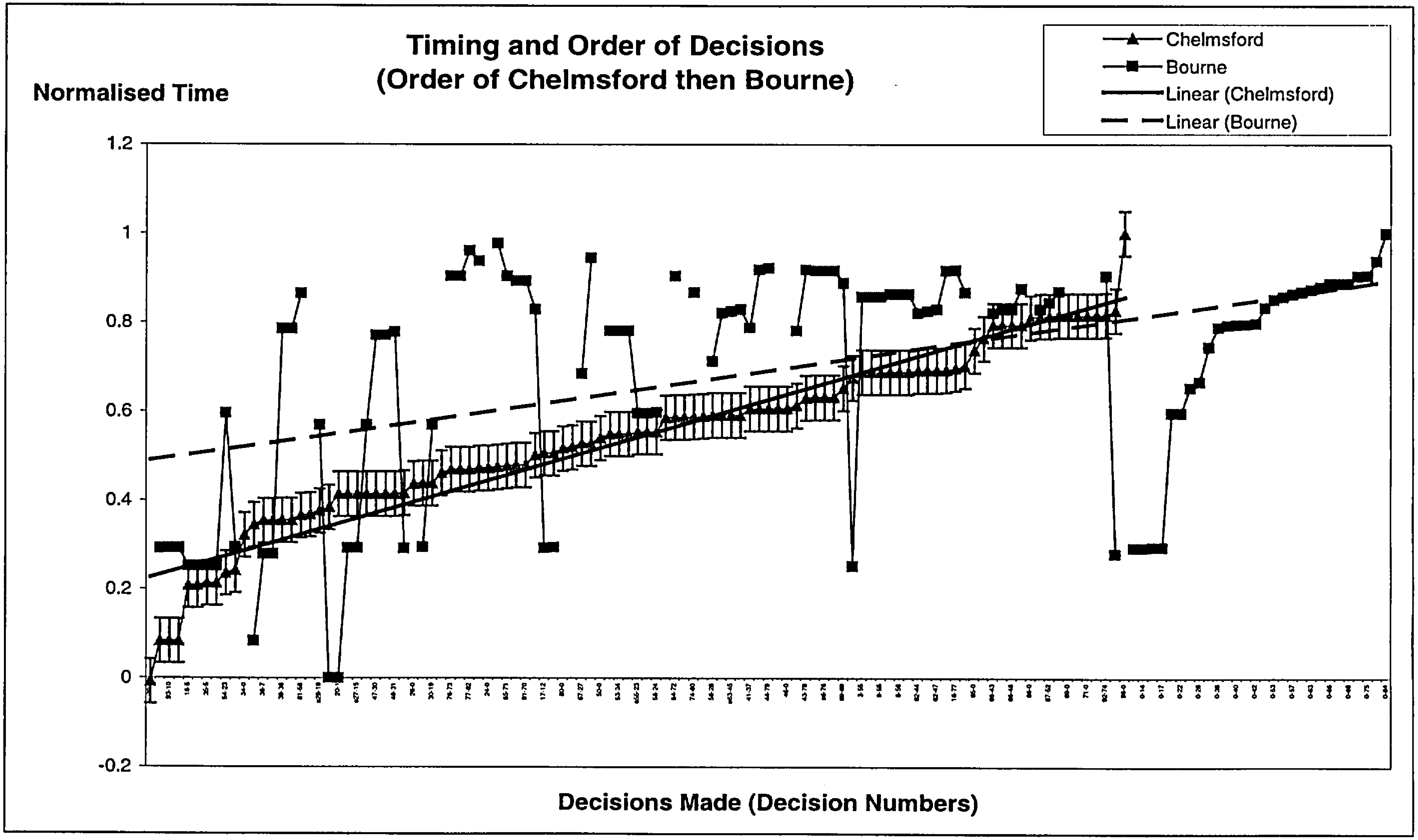


Figure J.3 – Chelmsford & Bourne Design Decisions Made Against Normalised Time

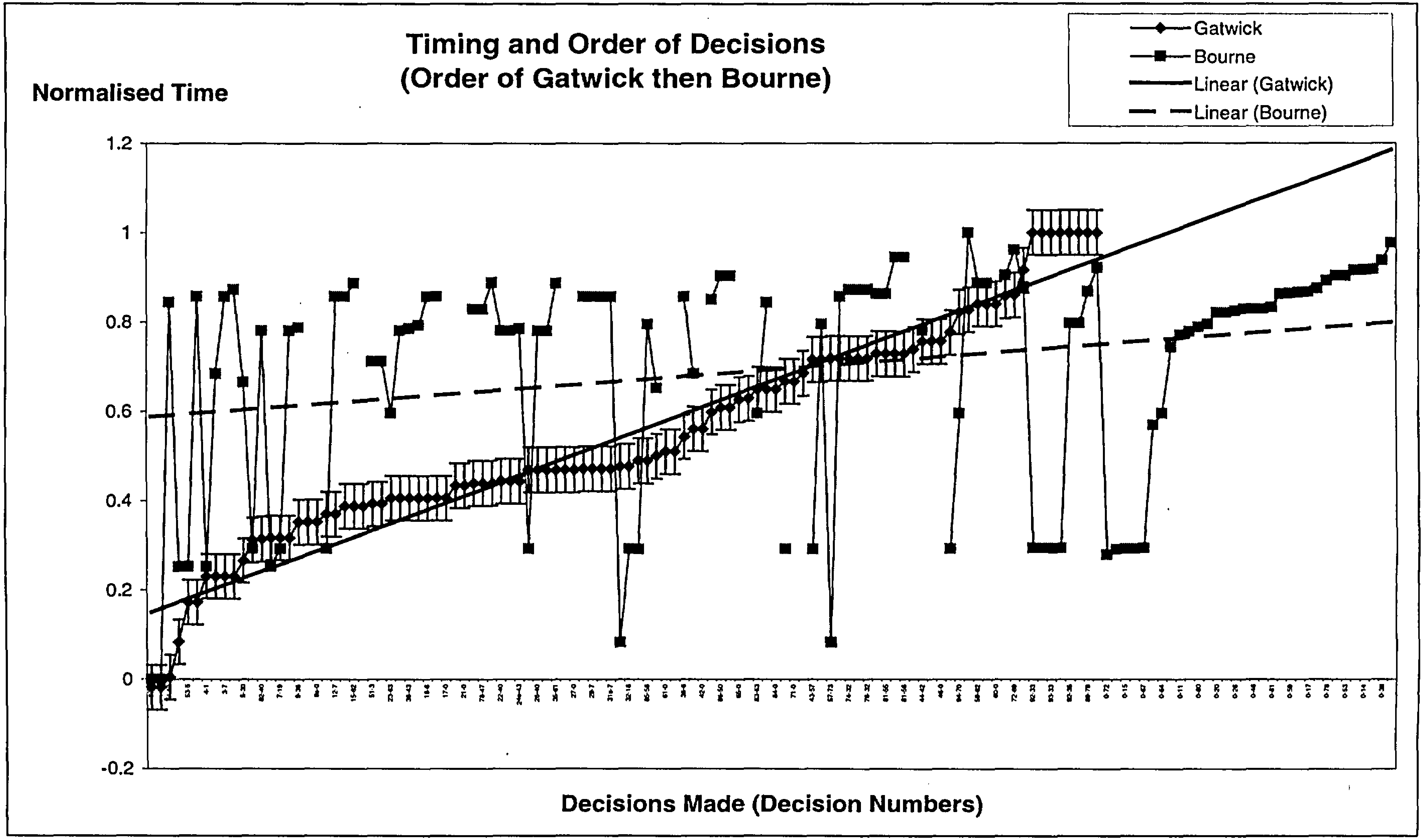


Figure J.4 – Gatwick & Bourne Design Decisions Made Against Normalised Time

[BLANK PAGE]

APPENDIX K

List of Figures

Figure K.1 – Cumulative Count of Design Decisions to be Made Against Normalised Time 2

Figure K.2 – Distribution of Design Decisions to be Made Against Normalised Time 2

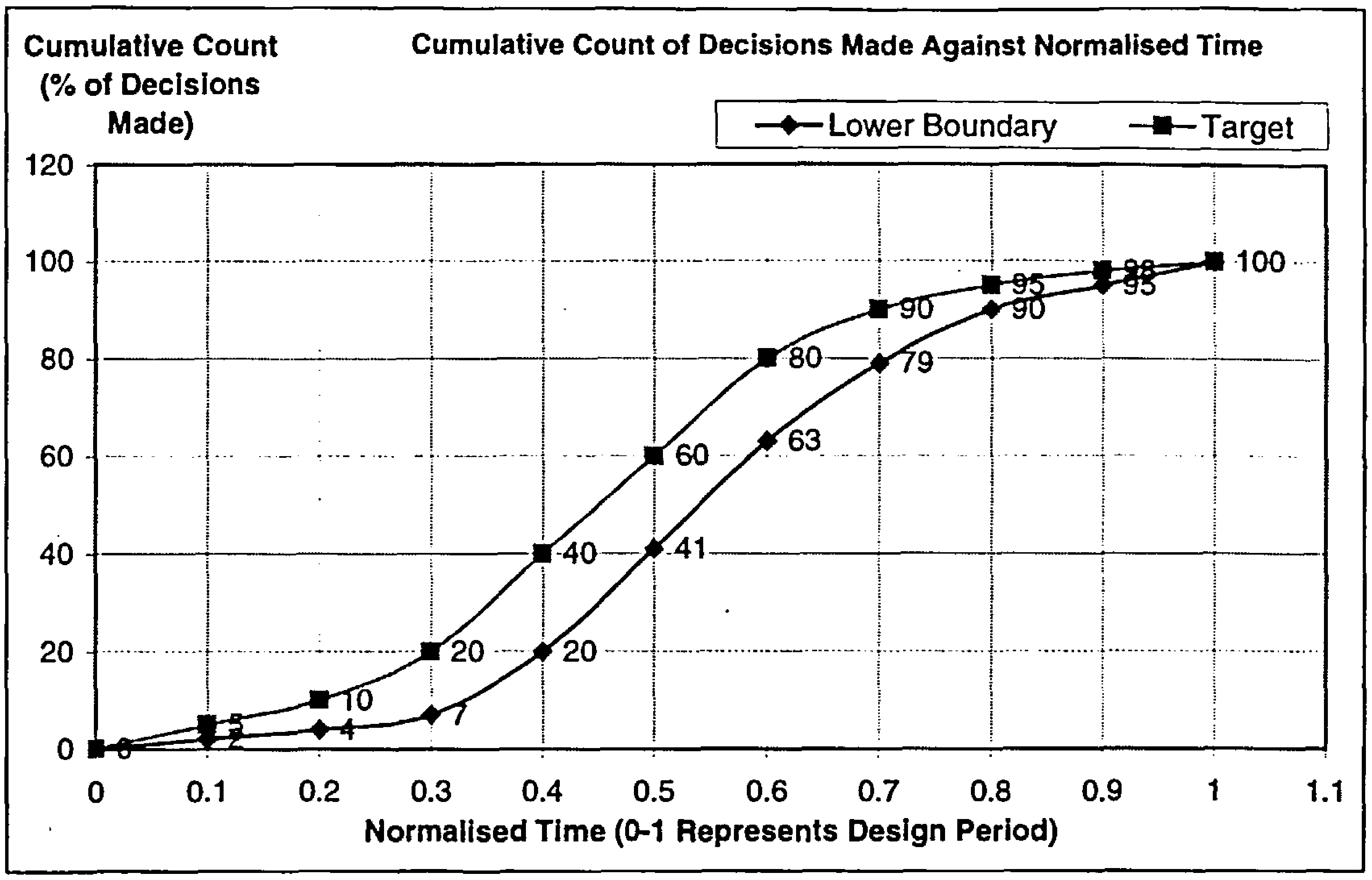


Figure K.1 – Cumulative Count of Design Decisions to be Made Against Normalised Time

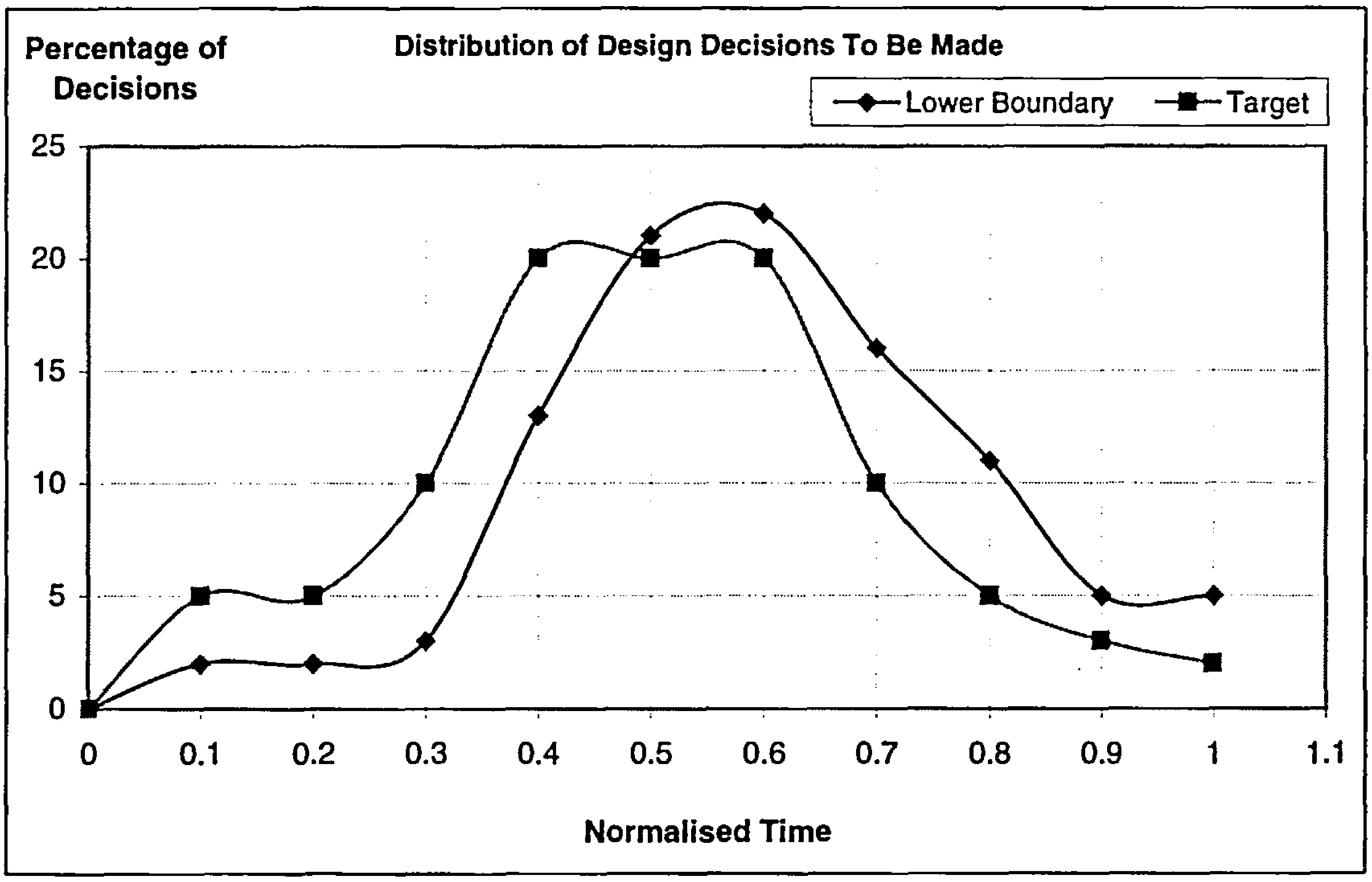


Figure K.2 – Distribution of Design Decisions to be Made Against Normalised Time