Transforming Traditional Mechanical and Electrical Construction into a Modern Process of Assembly

Peter F. Court

Crown House Technologies Limited
Bridge Place
Anchor Boulevard
Admirals Park
Dartford
Kent
DA2 6SN

Centre for Innovative and Collaborative Engineering
Department of Civil & Building Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

Loughborough University

Thesis Access Form

Copy No ……………………………… **Location**………………………………

Author Peter F. Court

Title Transforming Traditional Mechanical and Electrical Construction into a Modern Process of assembly

Status of access OPEN / ~~RESTRICTED~~ / ~~CONFIDENTIAL~~

Moratorium period: ………-………years, ending ………-……… / 200………-………

Conditions of access proved by (CAPITALS): …………………………………………………

Director of Research (Signature) ……………………………………………………………

Department of Department of Civil and Building Engineering

Author's Declaration: I agree the following conditions:

OPEN access work shall be made available (in the University and externally) and reproduced as necessary at the discretion of the University Librarian or Head of Department. It may also be copied by the British Library in microfilm or other form for supply to requesting libraries or individuals, subject to an indication of intended use for non-publishing purposes in the following form, placed on the copy and on any covering document or label.

The statement itself shall apply to **ALL** copies:

This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

Restricted/confidential work: All access and any photocopying shall be strictly subject to written permission from the University Head of Department and any external sponsor, if any.

Author's signature ……………………………… **Date** ………………………

Users declaration: for signature during any Moratorium period (Not Open work):
I undertake to uphold the above conditions:

Date	Name (CAPITALS)	Signature	Address

Loughborough University

Certificate of Originality

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgments or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Author's signature ………………………………………………………………

Date ………………………

TRANSFORMING TRADITIONAL MECHANICAL AND ELECTRICAL CONSTRUCTION INTO A MODERN PROCESS OF ASSEMBLY

By
Peter F. Court

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree of Engineering (EngD), at Loughborough University, United Kingdom

October 2009

Crown House Technologies Limited
Bridge Place
Anchor Boulevard
Admirals Park
Dartford
Kent
DA2 6SN

Centre for Innovative and Collaborative Engineering
Department of Civil & Building Engineering
Loughborough University
Loughborough
Leicestershire, LE11 3TU

ACKNOWLEDGEMENTS

Completion of this Engineering Doctorate Thesis was made possible by the help, advice, guidance and encouragement of many people over the last five years. Firstly I would like to thank my Academic Supervisors Dr. Christine Pasquire and Professor Alistair Gibb for their advice, guidance, research experience imparted and their unending support.

I would also like to thank my Industrial Supervisor, Mr Steve Wignall, without whom the completion of this research project would not have been possible. He kept faith in me all the way through on a large complex case study project.

The following people are also acknowledged for contributing to this research project, without them the design and implementation of the Construction System just would not have been achievable: David Bower, my previous Industrial Supervisor; Terry McRoy, CHt Planning and Production Control Manager; Alan Hart, CHt Offsite Manufacturing Manager and designer of assembly, transportation and installation frames (ATIF's); Wayne Pullen, CHt Construction and Logistics Manager and designer of workplace equipment; Andrew Green, CHt Commercial Manager; Paul Slade, CHt Maternity and Oncology Project Leader; Neil Grocott, Laing O'Rourke Maternity and Oncology Project Leader; Richard Porter, CHt Haywood Hospital Project Leader; Steve Lovern, Laing O'Rourke Haywood Hospital Project Leader and Alison Pope, Laing O'Rourke, who provided moral support and proof read my written English for this thesis. I would also like to acknowledge the help, support and assistance given to me by the Centre for Innovative and Collaborative Engineering staff, namely Jo Brewin and Sara Cowin. There are many other team members who have contributed to this research project, too many to mention, but each of them is acknowledged equally.

Dedicated to my Dad

Harold Arthur Court

1st September 1926 – 12th April 2008

God bless him…

ABSTRACT

This thesis presents the findings of a research project to develop and implement a Lean and agile Construction System on a case study project. The aim of the research project, for the sponsor company, was to improve its projects site operations, making them safer for the worker and improving effectiveness and productivity.

The findings have shown that the Construction System has proved to be a successful set of countermeasures that act as an antidote to the health, safety and productivity problems that exist in UK construction and that face the sponsor company. The System has been implemented on a large and complex mechanical and electrical case study project in the healthcare sector of UK construction. The outcome of this case study project shows that 37% less onsite labour was needed, meaning fewer workers were exposed to health and safety risks from site operations, leading to zero reportable accidents. Good ergonomics was achieved by focussing on workplace design, thus improving workers wellbeing, together with an improved quality of work for those required on site carrying out simpler assembly tasks. Productivity gains resulted by eliminating process waste, therefore reducing the risk of labour cost escalation that could otherwise have occurred. A 7% direct labour cost reduction was made meaning the labour budget allocation was maintained. Significantly, an overall productivity of 116% was achieved using the Construction System, which compares favourably to BSRIA's findings of an average overall productivity of only 37% when compared to observed best practice for the projects in that case study research.

The results include the benefits found from the use of an innovative method to assemble, transport, and install frameless, preassembled mechanical and electrical services modules, where a 93% reduction in onsite labour was achieved together with an 8.62% cost benefit.

No time slippage was experienced during onsite assembly to delay or disrupt other trades and the commissioning programme was not compressed that could otherwise have caused problems in handing over the facility to the customer. From a customer's perspective, the built facilities were handed over on-time, to their satisfaction and to budget.

The research has achieved two levels of innovation, one at a process level and one at a product level. The process innovation is the development and successful implementation of the Construction System, which is a combination of methods acting together as an antidote to the research problem. The product innovation is the development of the innovative method for assembling, transporting and installing frameless mechanical and electrical corridor modules, whereby modularisation can be achieved with or without an offsite manufacturing capability.

The System is built on Lean principles and has been shown to standardise the work, process and products to create flow, pull and value delivery. It is transferable across the sponsor company's business as well as the wider industry itself.

The transformation that has occurred is the creation of a step-change in undertaking mechanical and electrical construction work, which has realised a significant improvement in performance for CHt that has "Transformed Traditional Mechanical and Electrical Construction into a Modern Process of Assembly".

KEY WORDS

Lean, agile, construction, Health and Safety, productivity, ergonomics, innovation.

PREFACE

This thesis presents the research conducted between 2003 and 2008 to fulfil the requirements of an engineering doctorate (EngD) at the Centre for Innovative and Collaborative Engineering (CICE), Loughborough University, Leicestershire, United Kingdom. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the sponsor company). The project has specific objectives which are capable of making a significant contribution to the performance of the company.

The research project is conducted within an industrial context and sponsored by Crown House Technologies Limited (the company) which is a major provider of advanced mechanical, electrical and communications solutions within the construction sector in the United Kingdom.

The Engineering Doctorate is a four year postgraduate award and the core of the degree is the solution of significant and challenging engineering problems within an industrial context. The EngD is a radical alternative to the traditional PhD, being better suited to the needs of industry and providing a more vocationally oriented doctorate in engineering.

The EngD is examined on the basis of a 20,000 word discourse supported by publications and technical reports. This discourse is supported by 2 journal papers and three conference papers. It is to be read in conjunction with the appended papers providing a discourse of the research with in-depth technical detail presented in the academic papers. The papers are referenced within the text of this thesis.

USED ACRONYMS / ABBREVIATIONS

AEC	Architecture, Engineering and Construction
ATIF	Assembly, Transportation and Installation Frame
AVSU	Area Valve Service Unit
BFP	Building Fabric Process
BLS	Building Lifecycle Services
BMS	Building Management System
BOM	Bill of Materials
BSRIA	Building Services Research and Information Association
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CIBSE	Chartered Institute of Building Services Engineers
CICE	Centre for Innovative and Collaborative Engineering
CCTV	Closed Circuit Television
CHt	Crown House Technologies Limited
COSHH	Control of Substances Hazardous to Health
DfMA	Design for Manufacture and Assembly
EGLC	European Group for Lean Construction
ELV	Extra Low Voltage
EngD	Engineering Doctorate
EPSRC	Engineering and Physical Sciences Research Council
FJM	Fitting the Job to the Man
FMJ	Fitting the Man to the Job
HSE	Health and Safety Executive

HV	High Voltage
IBT	Intelligent Building Technologies
ICT	Information Communications Technologies
IGLC	International Group for Lean Construction
IIF	Incident and Injury Free
IMCRC	Innovative Manufacturing and Construction Research Centre
IMMPREST	Interactive Model for Measuring Preassembly and Standardisation in Construction
IPS	Integrated Plumbing System
IT	Information Technologies
JIT	Just-In-Time
LCI	Lean Construction Institute
LOR	Laing O'Rourke
LPF	Last Planner Facilitator
LPS	Last Planner System™
LV	Low Voltage
M&E	Mechanical and Electrical
MEP	Mechanical and Electrical Process
MR	Make Ready
MSD's	Musculoskeletal Disorders
MTO	Made to Order
MTS	Made to Stock
PDCA	Plan, Do, Check, Act
PFI	Private Finance Initiative
PLC	Public Limited Company

PPE	Personal Protective Equipment
RoSPA	Royal Society for the Prevention of Accidents
S&P	Standardisation and Pre-assembly
SERC	Science and Engineering Research Council
SOP's	Standard Operating Procedures
SPP	Specially Promoted Programme
UK	United Kingdom
USA	United States of America
WB	Working Backlog
WC's	Water Closets
WF	Working Frontlog
2D	2 Dimensional
3D	3 Dimensional
4D	Four Dimensional

TABLE OF CONTENTS

ACKNOWLEDGEMENTS .... **i**

ABSTRACT .... **v**

KEY WORDS .... **vi**

PREFACE .... **vii**

USED ACRONYMS / ABBREVIATIONS .... **ix**

TABLE OF CONTENTS .... **xiii**

LIST OF FIGURES .... **xix**

LIST OF TABLES .... **xxiii**

LIST OF PAPERS .... **xxv**

CHAPTER 1 INTRODUCTION **1**

1.1 INTRODUCTION 1

1.2 Background to the research 1

1.2.1 The general subject domain 1

1.2.1.1 Lean Thinking 1

1.2.1.2 Lean Construction 3

1.3 THE INDUSTRIAL SPONSOR 7

1.4 THE CONTEXT OF THE RESEARCH 9

1.5 STRUCTURE OF THIS THESIS 11

1.6 SYNOPSIS OF PAPERS 12

1.7 CHAPTER SUMMARY 14

CHAPTER 2 OVERARCHING AIM AND OBJECTIVES **15**

2.1 INTRODUCTION 15

2.2 OVERARCHING AIM 15

2.3 DEVELOPMENT OF THE RESEARCH AIM 16
2.4 RESEARCH OBJECTIVES 17
2.5 CHAPTER SUMMARY 18
CHAPTER 3 ADOPTED METHODOLOGY 19
3.1 INTRODUCTION 19
3.2 METHODOLOGICAL CONSIDERATIONS 19
3.3 METHODOLOGY DEVELOPMENT / REFINEMENT 21
3.3.1 The research process 21
3.4 METHODS / TOOLS USED 23
3.4.1 Action research 23
3.4.2 Literature search 24
3.4.3 Observational study 24
3.4.4 Ethnography 25
3.4.5 Experimental study 25
3.4.6 Research development process 26
3.5 CHAPTER SUMMARY 26
CHAPTER 4 THE RESEARCH UNDERTAKEN 29
4.1 INTRODUCTION 29
4.2 STEP 1: DEFINE THE SCOPE OF THE PROJECT 29
4.3 STEP 2: DATA COLLECTION FOR THE CURRENT STATE 30
4.3.1 Literature search 30
4.3.1.1 Health and Safety issues 30
4.3.1.2 Space issues 32
4.3.1.3 Crew relationship issues 32
4.3.1.4 Productivity issues 33

4.3.1.5 Worker availability and skills issues ... 36
4.3.2 Observational studies undertaken ... 36
4.3.3 Ethnographic study undertaken ... 38
4.3.3.1 Rich picture of ethnographic findings ... 38
4.3.4 Pilot experimental study ... 41
4.3.5 Summary of step 2 ... 42
4.4 STEP 3: DATA COLLECTION FOR THE FUTURE STATE ... 44
4.4.1 Literature search ... 45
4.4.1.1 Lean and agile manufacturing with postponement ... 45
4.4.1.2 Modular assembly ... 46
4.4.1.3 Reflective manufacture and quality of work ... 47
4.4.1.4 ABC parts classification ... 48
4.4.1.5 Ergonomics ... 49
4.4.2 Observational studies ... 51
4.4.3 Summary of step 3 ... 52
4.5 STEP 4: BREAKTHROUGH THINKING FOR DEVELOPMENT OF OPTIONS FOR ANALYSIS ... 52
4.5.1 The Construction System ... 53
4.5.2 Summary of step 4 ... 56
4.6 STEP 5: ANALYSIS AND EXPERIMENTATION OF OPTIONS FOR IMPLEMENTATION ... 56
4.6.1 Narrow and deep approach to implementation ... 58
4.6.1.1 The case study project ... 61
4.6.1.2 Conditions for success ... 62
4.6.1.2.1 The vision element for success ... 64

4.6.1.2.2 The skill element for success 64

4.6.1.2.3 The incentive element for success 64

4.6.1.2.4 The resources element for success 65

4.6.1.2.5 The action plan element for success 65

4.6.2 Turning theory into practice 66

4.6.2.1 Guiding principles, parameters and ground rules 68

4.6.2.2 Planning and production control 71

4.6.2.2.1 Reverse-pass scheduling 71

4.6.2.2.2 Onsite assembly with Week-Beat scheduling 73

4.6.2.2.3 Resource management 80

4.6.2.2.4 Production control 81

4.6.2.3 Design 82

4.6.2.3.1 Basic and detailed design 82

4.6.2.3.2 Digital prototyping 83

4.6.2.4 Procurement 84

4.6.2.5 Component manufacture 86

4.6.2.5.1 Logistics Strategy 86

4.6.2.5.2 ABC parts classification 87

4.6.2.5.3 Modular assembly - construction zone and plantroom modules (type A parts) 91

4.6.2.5.4 Postponement and parts kitting - construction zone and plantroom component flows (type B and C parts) 92

4.6.2.6 Onsite assembly 94

4.6.2.6.1 Inbound and outbound logistics 94

4.6.2.6.2 Workplace organisation 94

4.6.2.6.3 Training and induction ... 95
4.6.2.7 Commissioning ... 96
4.6.2.8 Construction System operation – bringing it all together ... 97
4.6.2.9 Summary of step 5 ... 99
4.7 STEP 6: SETTING OF REALISTIC OBJECTIVES AND MEASUREMENT OF SUCCESS FOR IMPLEMENTATION ... 99
4.7.1 Measurement of productivity outcomes ... 100
4.7.2 Measurement of Health and Safety outcomes ... 101
4.7.3 Summary of step 6 ... 102
4.8 STEP 7: ACTUAL IMPLEMENTATION AND TESTING SOLUTIONS ... 102
4.8.1 Commencement of the case study project ... 102
4.8.2 Summary of step 7 ... 105
4.9 STEP 8: FIRST RUN STUDY WITH RESULTS EMERGING ... 105
4.9.1 Progress in the sample period ... 105
4.9.2 Findings emerging from the sample period ... 106
4.9.2.1 Productivity and labour cost findings ... 106
4.9.2.2 Health and Safety findings ... 114
4.9.3 Lessons learned ... 117
4.9.4 De-skilling or re-skilling? ... 118
4.9.5 Summary of step 8 ... 121
4.10 CHAPTER SUMMARY ... 121
CHAPTER 5 FINDINGS AND IMPLICATIONS ... 123
5.1 INTRODUCTION ... 123
5.2 CONCLUSIONS ... 123
5.2.1 Achievement of the stated aim and objectives ... 123

5.2.2 Is it a Lean System? 125

5.3 CONTRIBUTION TO EXISTING THEORY AND PRACTICE 127

5.3.1 Interest generated by the System 128

5.4 IMPLICATIONS / IMPACT ON THE SPONSOR COMPANY 129

5.4.1 Company level implications 130

5.4.2 Customer level implications 132

5.4.3 Sponsor company implications / impact summary 132

5.5 IMPLICATIONS / IMPACT ON WIDER INDUSTRY 134

5.6 RECOMMENDATIONS FOR INDUSTRY / FURTHER RESEARCH 135

5.7 CRITICAL EVALUATION OF THE RESEARCH 136

5.8 CHAPTER SUMMARY 137

CHAPTER 6 REFERENCES 139

APPENDICES 151

Appendix A PAPER 1 (REFEREED, CONFERENCE) 153

Appendix B PAPER 2 (REFEREED, CONFERENCE) 175

Appendix C PAPER 3 (JOURNAL, PUBLISHED) 199

Appendix D PAPER 4 (REFEREED, CONFERENCE) 229

Appendix E PAPER 5 (JOURNAL, PUBLISHED) 249

Appendix F BSRIA BEST PRACTICE RECOMMENDATIONS 277

Appendix G SAFETY RESULTS FROM THE SAMPLE PERIOD 285

Appendix H LESSONS LEARNED FROM IMPLEMENTATION 291

H.1 PLANNING AND PRODUCTION CONTROL 291

H.2 POSTPONEMENT AND PARTS KITTING 291

H.3 WEEK-BEAT SCHEDULING 292

LIST OF FIGURES

Figure 3.1 Map of the research development process 27

Figure 4.1 Congested work site 39

Figure 4.2 Manual handling onto a scaffold 39

Figure 4.3 Various trades in the same workplace 39

Figure 4.4 Working on the floor 39

Figure 4.5 Improvised workbench 39

Figure 4.6 Congested and improvised workplace 39

Figure 4.7 Improvised workplace 39

Figure 4.8 Improvised workbench 39

Figure 4.9 Rich picture of the key words and phrases from the ethnographic study 40

Figure 4.10 Model of the Construction System (adapted from Court et al. 2009) 53

Figure 4.11 Shallow and wide approach, top down implementation (adapted from Arbulu and Zabelle 2006) 58

Figure 4.12 Business transformation process (adapted from Arbulu and Zabelle 2006).... 59

Figure 4.13 Narrow and deep approach, bottom up implementation (adapted from Arbulu and Zabelle 2006) 60

Figure 4.14 Site layout showing major new-build phases of the project 61

Figure 4.15 Project value chain with associated Construction System features 66

Figure 4.16 Traditional project value chain planning steps 72

Figure 4.17 Planning steps with reverse-pass approach 72

Figure 4.18 Maternity and Oncology construction zones 75

Figure 4.19 Construction zone assembly process (adapted from Court et al. 2009) 76

Figure 4.20 Mechanical and electrical process 1 (adapted from Court et al. 2009)........... 76

Figure 4.21 Close-scheduling MEP1 sub-process 77
Figure 4.22 Elevating the bottleneck sub-process; dry lining and studwork 78
Figure 4.23 Maternity and Oncology 46 week construction zone cycle-time programme . 79
Figure 4.24 Maternity and Oncology total 63 week cycle-time programme 80
Figure 4.25 MTO and MTS component flows into site 90
Figure 4.26 Mobile drawing and information board 95
Figure 4.27 Mobile workbench 95
Figure 4.28 Mobile parts storage unit (type C – MTS) 95
Figure 4.29 Mobile parts stillage (type B – MTS) 95
Figure 4.30 Construction System operation – bringing it all together 98
Figure 4.31 Mobile work cell for drainage crews in their own clear space 103
Figure 4.32 ATIF module ready for installation, type A materials (MTO) 103
Figure 4.33 Kit of parts for ventilation systems on mobile carrier, type B materials (MTO); inbound logistics 103
Figure 4.34 Outbound logistics (backhaul), returning mobile carriers for replenishment 103
Figure 4.35 Mobile carrier for pipework components, type B materials (MTS) 103
Figure 4.36 Ergonomic access equipment, walk-up mobile scaffold 103
Figure 4.37 Mobile carrier for modular wiring components, type B materials (MTO).... 104
Figure 4.38 Ergonomic materials handling equipment for dry-lining boards 104
Figure 4.39 Plantroom module, type A materials (MTO) 104
Figure 4.40 Plantroom module, type A materials (MTO) 104
Figure 4.41 Comparison of traditional approach, target Lean and agile approach, and actual hours booked, with actual hours minus unavoidable delays shown 109
Figure 6.1 Mobile kanban unit for cast iron drainage fittings 292
Figure 6.2 Redesigned type C parts centre 292

Figure 6.3 Revised MEP1 operations programme for Hub and Wards 293

LIST OF TABLES

Table 1.1 Project value proportions ... 10

Table 1.2 List of publications ... 13

Table 3.1 Fellows and Liu (2003) research process and the Productivity Press Development Team (2002) problem solving process ... 22

Table 4.1 BSRIA overall average productivity calculation ... 34

Table 4.2 Summary of primary issues ... 43

Table 4.3 Primary issues and countermeasures ... 57

Table 4.4 Elements for successful implementation (adapted from Arbulu and Zabelle, 2006) ... 63

Table 4.5 Component selection parameters and purpose ... 69

Table 4.6 Construction zone process and activity schedule ... 75

Table 4.7 Drawing definitions and responsibilities (from Parsloe 1997) ... 83

Table 4.8 ABC parts classification by MTS and MTO ... 88

Table 4.9 Comparison of estimated traditional costs to actual S&P costs (values are £000's) from Court et al. (2008) ... 107

Table 4.10 Table of measured benefits ... 111

Table 4.11 Budget versus actual direct labour hours during the sample period ... 113

Table 5.1 Analysis of potential labour cost reduction (values are £millions) ... 130

Table 6.1 BSRIA best practice recommendations and whether implemented ... 277

Table 6.2 Safety results from the sample period ... 286

LIST OF PAPERS

The following papers which are included in the appendices have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research.

PAPER 1 (SEE APPENDIX A)

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

PAPER 2 (SEE APPENDIX B)

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2006). Design of a Lean and agile Construction System for a large and complex mechanical and electrical project. Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.

PAPER 3 (SEE APPENDIX C)

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2009). Modular assembly with postponement to improve health, safety and productivity in construction. J. Practice Periodical on Structural Design and Construction, 14(2), 81-89.

PAPER 4 (SEE APPENDIX D)

Court, P., Pasquire, C., Gibb, A.G.F., (2008). Modular assembly in healthcare construction – a mechanical and electrical case study. Proceedings of the 16th annual conference of the International Group for Lean Construction, Manchester, United Kingdom, 2007.

PAPER 5 (SEE APPENDIX E)

Court, P., Pasquire, C., Gibb, A.G.F., (2009). A Lean and agile Construction System as a set of countermeasures to improve safety and productivity in mechanical and electrical construction. Lean Construction Journal, November 2009.

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

This chapter sets out the background to the research conducted in partial fulfilment of the requirements of an Engineering Doctorate (EngD) at the Centre of Innovative and Collaborative Engineering (CICE) Loughborough University. It introduces the general subject domain, the industrial sponsor, the context of the research and the structure of this thesis. In addition it provides a synopsis of each of the published papers that should be read in conjunction with the discourse.

1.2 BACKGROUND TO THE RESEARCH

1.2.1 The general subject domain

The general subject domain this research project is concerned with is the concept of Lean Thinking as originated in the manufacturing industry and in particular the motor industry. This includes the concept of agility which when coupled with Lean provides flexibility in delivering mass customised customer requirements. Furthermore, it is concerned with the application of Lean Thinking principles into construction. At the forefront of this are the Lean Construction Institute (LCI) and the International Group for Lean Construction (IGLC) the work of which is the main field that this research project belongs in.

1.2.1.1 Lean Thinking

As Womack and Jones (1996) state, Lean Thinking is a powerful antidote to muda. Muda is a Japanese term for waste and specifically any human activity which absorbs resources but creates no value and these are:

1 Mistakes which require rectification;

2 Production of items no one wants so that inventories and goods pile up;

3 Processing steps which aren't needed;

4 Movement of employees;

5 Transport of goods;

6 Waiting for upstream activities;

7 Goods and services that the customer does not want.

Lean comes from the ability to achieve more with less resource by the continuous elimination of waste as described. The concept of Lean is not restricted to manufacturing and applies to the whole enterprise including the supply chain, the new product development process and the provision of service. Womack and Jones (1996) define five Lean principles, which the author accepts are not presented as a theory (Koskela 2004) and are expressed here to demonstrate the essence of their message, which is to design a production system that will deliver a custom product instantly on order but maintain no intermediate inventories. The concepts include:

1 Specify what creates ***value*** from the customer's perspective;

2 Identify all the steps across the whole ***value stream***;

3 Make those actions which create value ***flow***;

4 Only make what is ***pulled*** by the customer Just-In-Time;

5 Strive for ***perfection*** by continually removing successive layers of waste.

The following are definitions for each of these key words and phrases:

1 ***Value*** **-** what the customer is willing to pay for (i.e. processes which transform the product, e.g.: bending, welding etc.);

2 ***Value stream*** - the sequence of processes to deliver value to the customer. (the complete value stream flows through the complete supply chain, from raw materials to finished goods);

3 ***Flow*** - the movement between value adding processes without delay or interruption;

4 ***Pull*** **-** activating a process when the customer wants to receive not when the supplier wants to provide;

5 ***Pursue perfection*** - work systematically to continuously improve every aspect of what is done, how it is done, who does it and what it is done with.

Other manufacturing concepts were explored in this research project with the techniques used in the design and development of the Construction System. These were modular assembly; Lean and agile manufacturing with postponement; reflective manufacture; period flow control and ABC parts classification. These concepts are described further in this thesis.

1.2.1.2 Lean Construction

According to the Lean Construction Institute (2009), Lean Construction is a production management based approach to project delivery, a new way to design and build capital facilities. Lean production management has caused a revolution in manufacturing design, supply and assembly. When applied to construction Lean changes the way work is done throughout the delivery process. Lean Construction extends from the objectives of a Lean production system - maximise value and minimise waste - to specific techniques and applies them in a new project delivery process and as a result:

- The facility and its delivery process are designed together to better reveal and support customer purposes. Positive iteration within the process is supported and negative iteration reduced;

- Work is structured by collaborative planning with those carrying out the work to maximise value and to reduce waste at the project delivery level;
- Efforts to manage and improve performance are aimed at improving total project performance which is more important than reducing the cost or increasing the speed of any activity;
- Control is redefined from “monitoring results” to “making things happen”. The performance of the planning and control systems is measured and improved.

In the paper "What is Lean Construction?" (Howell 1999), it is explained that managing the interaction between activities and the combined affects of dependence and variation is essential if we are to deliver projects in the shortest time. The first goal of Lean Construction must be to fully understand the underlying physics of production and the effects of dependence and variation along supply and assembly chains. Lean Construction rests on production management principles; the physics of construction. The result is a new project delivery system that can be applied to any kind of construction but is particularly suited for complex, uncertain and quick projects (Howell 1999).

The International Group for Lean Construction (IGLC), founded in 1993, makes up a network of professionals and researchers in Architecture, Engineering, and Construction (AEC) who feel that the practice, education and research of AEC have to be radically renewed in order to respond to the challenges ahead. The IGLC call their vision Lean Construction and the goal is:

> *“…to better meet customer demands and dramatically improve the AEC process as well as product. To achieve this, we are developing new principles and methods for product development and production management specifically tailored to the AEC industry, but akin to those defining Lean production that proved to be so successful in manufacturing”.*

The distinguishing feature of this group is its emphasis on theory. The IGLC view that the lack of an explicit theory of construction has been a major bottleneck for the progress in the AEC field. The clarification of the theoretical foundation of construction along with principles and methods emanating from the new foundation is the most effective means for the renewal of the AEC industry according to the IGLC. Annual conferences are the main activity of the group, structured around ten subgroups (Championships) addressing the following specific themes:

1 Theory;
2 Production System Design;
3 People, Culture and Change;
4 Supply Chain Management;
5 Product Development and Design Management;
6 Prefabrication, Assembly and Open Building;
7 Contracts and Cost Management;
8 Production Planning and Control;
9 Safety, Quality and the Environment;
10 Enabling Lean with Information Technology (IT).

There is also the European Group for Lean Construction (EGLC) organising workshops and group discussions within Europe. The EGLC represents a subgroup of the IGLC focussing on the local aspects of the implementation of Lean in Europe. The group makes up a network of researchers and practitioners conducting biannual workshops where areas of particular interest are discussed.

Through the LCI and the IGLC, Lean Construction differentiates itself by focusing on the whole construction process unlike other specialist societies which focus on vertical slices of it i.e. Health and Safety; Construction Economics; Environmental; Offsite Manufacturing etc. This can be seen in the breadth of the themes which are discussed. This research project draws heavily on the discussions from this group which have provided a valuable source of both theoretical and practical data with a global perspective. However, in the recent paper by Jorgensen and Emmitt (2008), the IGLC comes under fairly robust criticism from the authors for continuing to ignore the critical literature on Lean manufacturing and failing to recognise the potentially "dark side of Lean" (Green 1999) in the construction debate. Green argues that whilst the Lean rhetoric of flexibility, quality and teamwork is persuasive, critical observers claim that it translates in practice to control, exploitation and surveillance. However construction is only beginning the process of adopting manufacturing (Lean) techniques whereas manufacturing has been in this arena for over 50 years (pioneered by Toyota – Womack and Jones 1996). In fact, in construction, Lean Thinking is arguably the precondition for the next major step forward in accident reduction (Howell and Ballard 1999). In this response to Green (1999), the authors sum up with a proposal and pose the issue as a practical one; i.e. how can we gain the benefits of Lean principles and techniques without harming – or better yet enriching – those who do the work? Does reducing lead times, structuring work for flow, pulling materials and information, increasing plan reliability, and other Lean techniques cause workers to do less fulfilling jobs or work harder? "*We doubt it*", they finish.

This research project does in fact consider and incorporates alternatives to Lean production, especially reflective manufacture which is a socio-technical, person centred approach to vehicle manufacture that arose in Sweden at the Volvo Uddevalla plant. Its evolution is described by Granath (1998). This research found that Volvo, when looking into the development of production systems, looked into quality of work for the worker as well as efficiency of production. This is described later in this thesis.

Finally, in an important (to this research project) LCI white paper (no. 4) "The Design of Construction Operations" (Howell and Ballard 1999a), it is said that under Lean Construction, the design of the product and process occurs at the same time so factors affecting operations are considered from the first. Our aim, Howell and Ballard state, is to make the design of the operation explicit and to assure the issues affecting the operation are considered at the most appropriate time. This research project recognises this aim in that all of the issues affecting the operation of mechanical and electrical works will be considered and built-in to the design of the Construction System as is described in this thesis.

1.3 THE INDUSTRIAL SPONSOR

The industrial sponsor is Crown House Technologies Limited (CHt), a part of the Laing O'Rourke group of companies. CHt is a major provider of advanced mechanical, electrical and communications solutions within the construction sector in the United Kingdom (UK). It's expertise and credentials lie in serving customers in four primary sectors which are healthcare, education, transport and business critical systems (data centres). For the financial year 2007/2008 CHt's turnover was £349 million and for 2008/2009 will be £436 million. Its heritage stretches back almost 200 years to the original foundation in 1810 and has been at the forefront of the building services industry in the UK since then. CHt became part of the Laing O'Rourke Group (LOR) in 2004.

As well as delivering advanced mechanical and electrical (M&E) solutions CHt also provides the following services to its customers:

- Information Communications Technologies (ICT) – implementation of all IT networking and infrastructure, and systems such as CCTV, telephone and audio-visual communications;
- Intelligent Building Technologies (IBT) – implementation of building management systems (BMS), from heating and ventilation to fire detection and alarms;
- Building Lifecycle Services (BLS) – ongoing maintenance and monitoring of systems and equipment to ensure prolonged, problem-free performance.

CHt is one of the UK's leading manufacturers of offsite modular solutions[1] for building services which have been developed over the last 15 years and this is delivered through its wholly-owned manufacturing centre in the West Midlands, UK. Throughout the company Health and Safety is at the core of the business operations and CHt are committed to creating environments that are Incident and Injury Free (IIF). To this end they have created a culture of returning everyone who works with and for CHt, home safely at the end of each working day. In the last 16 years CHt has received RoSPA[2] Gold Medals, Presidents Awards and the Highly Commended Award for the highest standards of Health and Safety in the construction industry. In 2006 CHt was awarded the RoSPA Order of Distinction for Occupational Safety. As part of the LOR group, CHt shares the group's purpose and vision which is:

- "To be the company of first choice for all stakeholders – customers, employees, suppliers, trade contractors and the society in which we live…"
- "To challenge and change the poor image of construction worldwide…"

1 This capability has been reported in IGLC conference papers by Mawdesley and Long (2002) and Pasquire and Connolly (2002, 2003).

2 The Royal Society for the Prevention of Accidents.

- "With leanness and agility adopt processes to compete with world leading business…"

Added to this is the safety vision which states:

- The company holds Health and Safety as a core business value and is committed to creating a future free of incidents and injuries;
- While recognising the importance of discharging the full range of statutory obligations and duties, the company will take appropriate steps to meet and in many cases enhance these requirements;
- The company is prepared to invest whatever is necessary to drive improvement in health and safety, to ensure everybody returns home safely. "Failure to do so renders the company valueless".

1.4 THE CONTEXT OF THE RESEARCH

For CHt, labour cost is one of the largest variables which can have a direct influence on the financial outcome of its projects (Hanna et al. 2002, Court et al. 2005). Labour cost control is therefore a critical function for its profitability. Labour cost is a function of productivity on CHt's projects, so taking measures to improve this will allow the company to have greater measure of control over this variable.

As a project based organisation CHt's business is the sum of all its projects therefore the business performance is dependant upon the performance of its projects in aggregate. In the current year, CHt has on average 71 projects in progress with the value proportions of its projects when tendered presented in table 1.1.

Table 1.1 Project value proportions

Project value element	Proportion of project value
Labour	17%
Plant (hired plant and equipment)	1%
Materials	16%
Sub-contractors	34%
Preliminaries[3]	22%
Margin	10%
Total	**100%**

As can be seen the labour element represents 17% of the value of a project. When calculating this across its subcontracted element[4] which is 34%, total labour percentage is 23%[5] (17% plus 17% of 34%).

CHt's turnover for the financial year 2007/2008 was £349 million, of which a total of £80.27 million was forecast to be spent on labour including subcontractor's labour (23% of £349 million). This is the biggest variable the company has to control in order to ensure margin is delivered into the business. For CHt, the increased cost of labour on recently completed major projects has had a direct impact on the financial outcome of those projects and because of the

3 Preliminaries are the cost of operating the site under specified conditions and in accordance with the contractors plan for the progress of the work and for storage and movement of material, plant and site establishment.

4 Assessed to be the same as CHt labour content at 17%. The percentage of labour for sub-contractors in at the low end of the scale and could be as high as 25%. This is because sub-contactors do not provide capital plant and therefore the ratio of labour to the sub-contract value is higher (source: discussion with Mr. Peter Hession, a director of CHt).

5 In Hawkins (1997) it states labour costs typically constitute 30% of overall project M&E costs. CHt's labour at 23% of project value (including subcontractors) calculates to 26% of project cost (when deducting margin), which approximates to Hawkin's findings of 30%.

scale of the cost overruns, CHt itself (Court et al. 2005). These projects were run in a traditional manner with no specific Lean interventions being made.

CHt also wants to improve its health and safety performance across the business. They are not immune from the construction environment in which they operate and indeed suffer in the same way as the wider M&E industry. Whilst CHt's safety records have deserved and indeed won safety awards and it is profitable, there is always room for improvement. One accident is one too many and profit improvement is always resonant in the board room. Therefore, CHt sees this research project as another means to improve health and safety for its workers and to ensure that everyone goes home safely at the end of a productive days work, especially as the research project specifically seeks to improve workers health, safety and productivity as will be shown.

This research project therefore proposes that Lean techniques, when imposed upon a project, are an antidote to the health, safety and productivity problems that CHt faces in the M&E industry, within the UK construction sector.

As a point to note, the author is the M&E Project Leader for CHt on the case study project and is submitting this thesis as part of the award for the Engineering Doctorate.

1.5 STRUCTURE OF THIS THESIS

The structure of the thesis is presented below informing the reader of the content of each chapter of the thesis.

Chapter one introduces the general subject domain, the industrial sponsor and the context of the research.

Chapter two presents the overarching aims and objectives of the research.

Chapter three discusses the methodological considerations, methodology development and refinement and the methods and tools used for the research undertaken.

Chapter four describes the main steps of the research undertaken and presents the results of the implementation of the Construction System on a case study project.

Chapter five discusses the key findings of the research, the contribution to existing theory and practice, the implications and impact on the sponsor company and on the wider industry. It concludes with recommendations for industry and further research with a critical evaluation of the research undertaken.

Appendix A-E presents the five academic papers published during this research. These papers are an essential part of the research and should be read in conjunction with this thesis.

Appendix F-H contains the BSRIA best practice recommendations which this research project takes particular cognisance of, the safety results during the sample period and certain important lessons learned from the implementation of the Construction System.

1.6 SYNOPSIS OF PAPERS

To summarise and disseminate the research findings of this project, five scientific papers have been published during the period and these are presented in table 1.2. Full bibliographical references are provided, together with the status of each paper, and a brief description of their contribution to the fulfilment of the research aim and objectives. Each paper has been indentified by a paper number and the corresponding appendix reference.

Table 1.2 List of publications

Paper ID	Title	Journal/Conference	Status	Full bibliographical references and Paper description
Paper 1, Appendix A	Lean as an antidote to labour cost escalation on complex mechanical and electrical projects.	Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.	Published	Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005. This paper proposes that Lean techniques, when imposed upon a project can be an antidote to the causes of poor productivity, and therefore prevent labour cost escalation, along with its impact on the project's profitability. This is tested in a pilot study project.
Paper 2, Appendix B	Design of a Lean and agile Construction System for a large and complex mechanical and electrical project.	Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.	Published	Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2006). Design of a Lean and agile Construction System for a large and complex mechanical and electrical project. Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006. This paper describes the development of the Construction System and proposes a Lean and agile production System model which is to be implemented on a case study project.
Paper 3, Appendix C	Modular assembly with postponement to improve health, safety and productivity in construction.	J. Practice Periodical on Structural Design and Construction.	Published	Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2009). Modular assembly with postponement to improve health, safety and productivity in construction. J. Practice Periodical on Structural Design and Construction, 14 (2), 81-89. This paper presents the outcome of an engineering study as part of the detailed design of the supply chain component of the Construction System. This combines modular assembly with a postponement function.
Paper 4, Appendix D	Modular assembly in healthcare construction – a mechanical and electrical case study.	Proceedings of the 16th annual conference of the Int. Group for Lean Construction, Manchester, United Kingdom, 2008.	Published	Court, P., Pasquire, C., Gibb, A.G.F., (2008). Modular assembly in healthcare construction – a mechanical and electrical case study. Proceedings of the 16th annual conference of the International Group for Lean Construction, Manchester, United Kingdom, 2008. This paper reports on the findings using IMMPREST software as a tool for assessing the benefits derived from the use of modular offsite assembly versus a traditional onsite method.
Paper 5, Appendix E	A Lean and agile Construction System as a set of countermeasures to improve safety and productivity in mechanical and electrical construction.	Lean Construction Journal.	Published	Court, P., Pasquire, C., and Gibb, A.G.F. (2009). A Lean and agile Construction System as a set of countermeasures to improve safety and productivity in mechanical and electrical construction. Lean Construction Journal, November 2009. This paper presents certain aspects of the findings following implementation of the Construction System on the case study project during a sample period.

1.7 CHAPTER SUMMARY

This chapter has set out the background to the research conducted and has introduced the general subject domain which is Lean Thinking and Lean Construction. It has introduced the industrial sponsor, CHt, together with the context of the research for them. Finally, the structure of this thesis has been described with a synopsis of each of the published papers contained in appendix A-E of this thesis.

CHAPTER 2 OVERARCHING AIM AND OBJECTIVES

2.1 INTRODUCTION

This chapter sets out the aim and objectives of the research undertaken together with the development of the research aim which has occurred since this project commenced.

2.2 OVERARCHING AIM

The overarching aim of this research project is to develop and implement a new way of working for CHt in order to improve the performance of its projects site operations, making them safer for the worker and to improve productivity as a countermeasure to the problems that CHt faces in the M&E industry within the UK construction sector.

Safety is at the core of the company and according to the Business Leaders *"…it is an absolute right for people to return home safely at the end of a productive day's work"* and *"failure to do so render the company valueless."* The key words here being *safely* and *productive,* these are therefore at the core of the aim of this research project which is to design and implement a safer and more productive way of working on site (i.e., the countermeasures[6]). It takes a holistic approach to develop and implement a Lean and agile Construction System to transform traditional M&E construction into a modern process of assembly to the benefit of the worker, the company and the industry. Further than this, CHt see this research project as a vehicle not only to deliver performance improvement but, when embedded and repeated across all of its projects, for it to become a source of competitive

[6] A countermeasure is defined by Oxford English Dictionary (2009) as an action taken to counteract a danger or threat. The threat to the company is the primary issues faced in UK construction, i.e. the research problem.

advantage which will provide a stable flow of profitable safe projects leading to an increase in the company's enterprise value[7].

Quality is an important aspect of the work that CHt carries out and is inextricably linked to the performance of its projects as is health, safety, productivity and cost. That said it is not the intent to measure quality outcomes as a result of implementing the System described in this thesis as the case study project is subject to the ISO 9001 quality systems and procedures that CHt are accredited to and are audited against. The case study project has a quality system in place which is audited by a third party organisation as part of CHt's ongoing annual accreditation process. The outcomes of this quality system and the actual audits are not reported in this thesis.

2.3 DEVELOPMENT OF THE RESEARCH AIM

Initiated in 2003, the initial intent of the research was to develop ways to reduce the costs of delivering projects for the sponsor company who were at that time owned by the construction company, Carillion PLC. It was thought then that by improving productivity on its construction sites, CHt could have some control over the largest cost variable that can influence the financial outcome of its projects, which is labour cost. If labour cost escalates above that which is estimated for the project then margin slippage can occur. This is because productivity of labour has a direct influence on labour cost and therefore the projects financial outcome as was discovered in the initial stages of the research. In these initial stages of the research looking into the factors that influence productivity it became evident that these factors also had an effect on the health and safety of workers, so by overcoming these factors then the health and safety of CHt's workers could also be improved together with

[7] Enterprise value is defined as a company's worth as a functioning entity, or its acquisition cost.

productivity. This was coincidental with a change of ownership of CHt from Carillion to LOR in 2004. With this came LOR's purpose and vision statements and the Incident and Injury Free (IIF) programme, the objective of which is to send everyone home safely after a productive days work. This is not to say that CHt or Carillion were not interested in health and Safety at that time, far from it, but it coincidentally joined productivity with health and safety improvements as an aim for this research project as they are so inextricably linked together and this matched the requirements of LOR's IIF programme.

2.4 RESEARCH OBJECTIVES

The overall objective was to identify the issues that cause poor productivity and health and safety performance in M&E construction and to develop a conceptual system using Lean methods from other industries that can overcome these issues. Following this, to then develop the conceptual Construction System into real and meaningful methods that are able to be applied and tested on a case study project during a sample period. This was to be achieved with the following six research objectives:

Objective 1: To reveal and understand the issues that leads to poor health, safety and productivity performance;

Objective 2: To reveal and understand Lean methods in use in other industries;

Objective 3: To develop a conceptual Construction System that adopts Lean methods from other industries that can be applied to M&E construction;

Objective 4: To turn the theory of the developed System into practice with real and practical methods that is able to be applied to a case study project in the real world;

Objective 5: To set realistic and achievable targets against which the System can be measured during implementation;

Objective 6: To implement the System on a live case study project and to measure the results emerging during the implementation.

2.5 CHAPTER SUMMARY

This research project has the overarching aim to develop and implement a new way of working for CHt in order to improve the performance of its projects site operations, making them safer for the worker and to improve productivity. It seeks to challenge and change traditional construction thinking and to develop and implement a system to transform traditional M&E construction into a modern process of assembly. This system will be called the "Crown House Construction System." The Construction System is defined as a pre-assembly methodology that will demonstrate the feasibility of creating and implementing new processes in M&E construction. The transformation expected is the creation of a step-change in undertaking M&E construction work and to realise significant improvements in performance. It will industrialise[8] traditional M&E construction using Lean and agile manufacturing techniques making the work safer, more effective and productive.

[8] Industrialisation is the development of an industry on an extensive scale (Visual Thesaurus 2009).

CHAPTER 3 ADOPTED METHODOLOGY

3.1 INTRODUCTION

The success and validity of any research critically depends upon the appropriate selection of research methods (Fellows and Liu 2003). This chapter sets out the research methodological considerations, the research methodology development and refinement, the methods and tools used and the role of these methods within the research methodology chosen and the development of the research process undertaken.

3.2 METHODOLOGICAL CONSIDERATIONS

As has been described, the overarching aim of this research project for CHt was to develop and implement a new way of working in order to improve its site operations, making them safer for the worker and to improve productivity as a countermeasure to the prevailing conditions in UK construction that CHt faces. The problems that cause poor health, safety and productivity performance exist on the construction site where the work is performed by CHt's workforce and that of its and other interfacing sub-contractors. These were to be overcome with specifically designed countermeasures as an antidote to these problems that exist. The construction site was therefore a main focus of attention for this research project.

According to The Productivity Press Development Team (2002), when solving productivity problems it is essential that you actually go to the work site and closely examine the operation or process being improved so that you do not make incorrect assumptions about the actual causes which will lead you to solve the wrong problem, fail to find the root cause and therefore have a return of the problem later or miss the real issues in some other way. Also, and significantly in the world of Lean according to Ohno (1988), the production plant is manufacturing's major source of information, it provides the most direct, current and stimulating information about management, this is what Ohno called his plant-first principle. Liker (2004), describing The Toyota Way 14 Management Principles, describes principle 12 which is to go and see for yourself to be able to thoroughly understand the situation. The key points of this principle are described as follows:

- Solve problems and improve processes by going to the source and personally observing and verifying data rather than theorising on the basis of what other people or the computer screen tell you;
- Think and speak based on personally verified data;
- Even high-level managers and executives should go and see things for themselves so they will have more than a superficial understanding of the situation.

This research project did not seek to measure specific task productivity performance of the M&E activities undertaken by CHt; enough of this has been done already (Hawkins 1997). The author decided that there was no value in repeating the research Hawkins had already undertaken as CHt was a sponsor in this study and contributed to the research at that time. Rather the choice was to accept its findings and to take cognisance of the best practice recommendations made as a basis for this research project. With this in mind and using Ohno's plant-first principle, combined with the problem-solving method from the Productivity Press and Toyotas principle 12, a site-first principle[9] was used. The site is to construction in the same way as the plant is to manufacturing. As Ohno describes his plant-first principle as being manufacturing's major source of information, this is the same for the construction site. It is the culmination of all the construction processes and what is given to the customer (or end-user) when it is finished. Also, are workers the only participants in the

[9] Named by the author for this combination of methods.

building process directly generating value to the customer? Larsen et al. (2003) argued this point and these were the reasons for the principle method of this research project which sought to focus on the worker and the worker's environment. It was only concerned with M&E workers and those of key interfacing trades insofar as they apply. This research could only be done on the construction site itself by personal observation, verification and to think and speak on this personally verified data.

3.3 METHODOLOGY DEVELOPMENT / REFINEMENT

3.3.1 The research process

In the 1980's The Science and Engineering Research Council (SERC), the forerunner of the Engineering and Physical Sciences Research Council (EPSRC) in the UK, held a Specially Promoted Programme (SPP) in Construction Management and developed their view of the research process relating to the SPP (Fellows and Liu 2003). Also, when considering standardisation, the Productivity Press Development Team (2002) describes a complete sequence for solving problems. The major steps in each of these processes are shown in table 3.1.

Table 3.1 Fellows and Liu (2003) research process and the Productivity Press Development Team (2002) problem solving process

Fellows and Liu (2003)		Productivity Press (2002)	
Step 1:	Identify the problem.	Step 1:	Describe the problem.
Step 2:	Define the problem.	Step 2:	Organise and categorise the descriptive data.
Step 3:	Establish objectives.	Step 3:	Prioritise the descriptive data.
Step 4:	Literature review.	Step 4:	Select the most important problem.
Step 5:	Develop research plan.	Step 5:	Establish a goal.
Step 6:	Review literature.	Step 6:	Go to the work site to study the problem first hand.
Step 7:	Data collection.	Step 7:	Make illustrations and detailed descriptions of the current conditions to study the problem more closely.
Step 8:	Data analysis.	Step 8:	Devise improvement plans.
Step 9:	Produce report.	Step 9:	Test a temporary solution.
		Step 10:	Devise and test permanent solutions.
		Step 11:	Check whether the problem still exists.
		Step 12:	Firmly implement the successful temporary improvement and set target date for working out the permanent improvement.
		Step 13:	Establish new standards.

The actual process selected was an optimisation of both of these and the research process for this project had the following nine major steps[10]:

Step 1: Define the scope of the project (identifying and overcoming the research problem);

[10] This research process was agreed by the author's academic supervisors as part of the end of first year report for the Engineering Doctorate.

Step 2: Data collection for the current state (the situation today) including observation of current practice with action research and a literature search for further evidence of the current state;

Step 3: Data collection for the future state (the vision of how things could be) including literature search for the future vision, looking outside the industry for best practice and innovation and inside the industry for best practice and innovation. This will include more than a literature search and will include action research inside other industries;

Step 4: Breakthrough thinking for development of options for analysis;

Step 5: Analysis and experimentation of options for implementation;

Step 6: Setting of realistic objectives and measurement of success for implementation (how will we know it's working when we have done it);

Step 7: Actual implementation and testing solutions;

Step 8: First run study with results emerging;

Step 9: Production of a thesis for this Engineering Doctorate.

The research methods and tools used to conduct this research project are now described.

3.4 METHODS / TOOLS USED

The principle methods used within this research process were action research; literature search; observational study; ethnography and experimental study.

3.4.1 Action research

Coghlan and Brannick (2003) define action research as involving a cyclical process of diagnosing a change situation or problem, gathering data, taking action, and then fact finding about the results of that action in order to plan and take further action. Also, the key idea of action research is that it uses a scientific approach to study the resolution of important social and organisational issues together with those who experience these issues directly. Action research spanned all of the steps in this research project in order to diagnose the research problem, gather data, take action and fact find results to allow further action to be taken.

3.4.2 Literature search

According to Fellows and Liu (2003), an essential early stage of virtually all research is to search for and to examine potentially relevant theory and literature. Theory and literature are the results of previous research projects. They define theory as the established principles and laws which have been found to hold, whereas in this context they define literature as concerning the findings from research which has not attained the status of theory. As Fellows and Liu state, it often represents findings from research into particular applications of theory. A literature search has been used in this research project to allow the author to understand past and current theory and practice required related to the context of this study. This research method also spanned all of the steps in the research project to enable the author to keep up to date with potentially relevant theory and literature.

3.4.3 Observational study

According to Yin (2003), observational evidence is often useful in providing additional information about the topic being studied. If a case study is about a new technology then observations of the technology at work are invaluable aids for understanding the actual uses of the technology or the problems encountered. Also, the condition of buildings or work spaces will indicate something about the climate or impoverishment of the organisation (Yin 2003). Observational studies have been used in this research project which allowed the author to go to the source and personally verify data (Liker 2004), and to provide direct information and feedback on current practice on construction sites and inside other industries related to this project.

3.4.4 Ethnography

In order to be able to think and speak on personally verified data (Liker 2004), an ethnographic study method was also used. Ethnography is a style of research rather than a single method and uses a variety of techniques to collect data (Cassell and Symon 2004). They defined this style of research as the study of people in naturally occurring settings or 'fields' by means of methods which capture their social meanings and ordinary activities, involving the researcher participating directly in the setting (if not also in the activities) in order to collect data in a systematic manner but without meaning being imposed on them externally. The purpose of this study was for the author to become a participant in the site process in order to be immersed in the day-to-day site activities and not just be an observer. This method allowed the author to understand people's actions and their experiences of the world in natural settings as they occurred independently of experimental manipulation[11].

3.4.5 Experimental study

An experimental study was the chosen method to test the Construction System on the case study[12] project. According to Yin (2003), experiments are done when an investigator can manipulate behaviour directly, precisely and systematically. This can occur in a laboratory setting and in this context the North Staffordshire Hospitals Project (the case study project)

11 Where deliberate intervention is made by the researcher/s which may affect the outcome of the study being undertaken.

12 The term case study is used in this thesis to describe the project where the Construction System will be tested, not the research method itself. It is accepted that the term "case study" is a recognised research method but where no control over behavioural events is required (Yin 2003).

was the large real-life laboratory where the author manipulated behaviour directly, precisely and systematically by imposing the Construction System as a set of countermeasures to what would otherwise have occurred naturally. A small scale experimental study was also used in the early stages of the research project to test Lean interventions in a pilot study. The experimental studies undertaken in this research project used the concepts of hypothesis; independent variables; dependent variables and measurement (Smith et al. 2003). How these concepts relate to the experimental study undertaken were described in Court et al. 2005 (paper 1 contained in appendix A), and in chapter 4 of this thesis.

3.4.6 Research development process

Having described the aim and objectives of the research project in the last chapter, and the methodology and methods used to achieve the objectives, figure 3.1 presents a map of the research development process connecting the research objectives with the steps in the research process, the research methods used and then to the EngD deliverables which are the five published papers and this thesis.

3.5 CHAPTER SUMMARY

This chapter has described the research methodological considerations, its development and refinement and the research methods used. A map of the research development process has been presented which sets out the six research objectives, their connection to each step in the research process, the research methods used and their role in the process, and finally the findings from the steps in the process that were then published as scientific papers in refereed journals and conferences (see Appendix A-E). The next phase is the actual research undertaken and this is described in the next chapter.

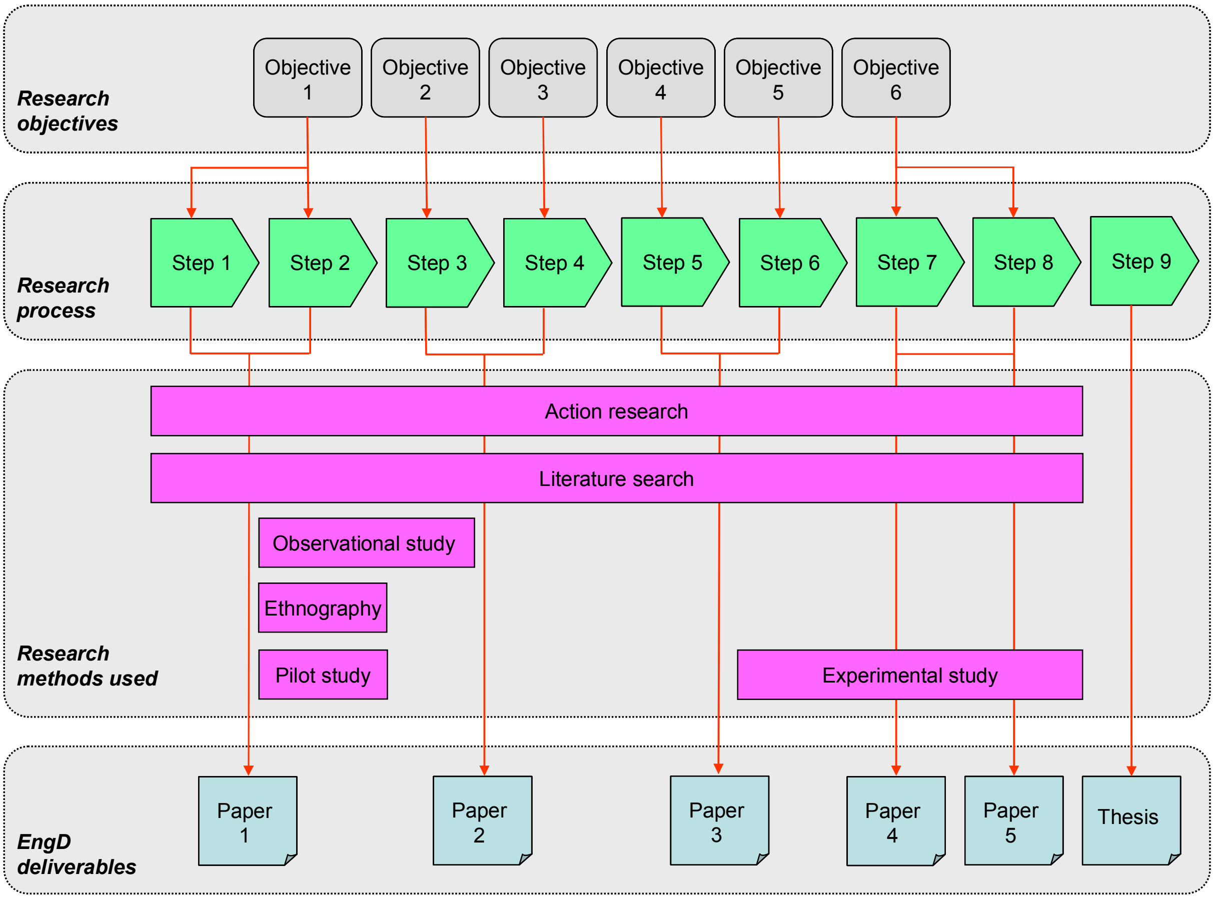

Figure 3.1 Map of the research development process

CHAPTER 4 THE RESEARCH UNDERTAKEN

4.1 INTRODUCTION

The research undertaken followed the process and steps described in chapter 3, Adopted Methodology and these steps were:

Step 1: Define the scope of the project (identifying and overcoming the research problem);

Step 2: Data collection for the current state (the situation today);

Step 3: Data collection for the future state (the vision of how things could be);

Step 4: Breakthrough thinking for development of options for analysis;

Step 5: Analysis and experimentation of options for implementation;

Step 6: Setting of realistic objectives and measurement of success for implementation;

Step 7: Actual implementation and testing solutions;

Step 8: First run study with results emerging;

Step 9: Production of a thesis for this Engineering Doctorate.

This chapter describes the research undertaken in each of these steps.

4.2 STEP 1: DEFINE THE SCOPE OF THE PROJECT

The scope (also the aim) of this research project was to develop a way of working on site that will overcome the issues of poor productivity and safety performance (the research problem) that the construction industry and in particular the M&E work which CHt undertakes. This has been termed *"Transforming Traditional Mechanical and Electrical Construction into a Modern Process of Assembly"* created by the development of the "Crown House Construction System." This title was inspired by the "Toyota Production System" but the research did not seek to replicate the Toyota Production System itself. Once developed this Construction System was tested on a live case study project, the selection of which is described later in this thesis.

4.3 STEP 2: DATA COLLECTION FOR THE CURRENT STATE

Step 2 of the research process involved collecting data to identify the current state (the situation today). This step commenced the action research method, and included a literature search, observational studies, ethnography and a pilot experimental study.

4.3.1 Literature search

The findings of the literature search supported the development of the Construction System by revealing the issues that created the research problem. The primary issues identified concerned health and safety; space (congestion onsite); relationships between crews that caused interference or delay; productivity; worker availability and skills.

4.3.1.1 Health and Safety issues

According to the Health and Safety Executive (HSE) 2007, 2.2 million people work in Britain's construction industry making it the countries biggest industry, it is also one of the most dangerous. In the last 25 years over 2,800 people have died from injuries they received as a result of construction work, many more have been injured or made ill. The HSE (2007a) identified that construction also has the highest rate of musculoskeletal disorders (MSD's); these are mostly back injuries from manual handling. There were 56,000 work related MSD cases in construction in 2004/5. Handling injuries (to employees in 2004/5) accounted for 38% of over 3 day injuries and 15% of major injuries. In their research into MSD's, the HSE (2007b) has identified areas that can create a risk which includes; repetitive and heavy lifting;

bending and twisting; repeating an action too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment (e.g. hot, cold); psychosocial factors (e.g. high job demands, time pressures and lack of control); not receiving and acting upon reports of symptoms quickly enough.

Considering other health and safety factors, occupational health has been ignored in favour of the more immediate, high impact occupational safety (Gibb 2006). Gibb argues that occupational health incidents are to be considered as "slow accidents" – the period over which the incident occurs may be lengthy and may creep up on you unawares. This implies that the result will be the same as an occupational accident; in that a worker gets injured but it just takes longer. Gibb's keynote paper reports that in the UK 4,500 construction workers are absent from work every day because of injuries caused by accidents, but there are 11,000 construction workers off sick at any one time with a work-related illness. Gibb reports that in the UK, the construction industry employs around 10% of the working population but causes a much greater percentage of occupational ill health. Furthermore, it is reported by Gibb, MSD's which, according to the limited evidence available, may be the most widespread problem in the industry.

Research conducted for its Better Backs Campaign (HSE 2000) found that a change to prefabricated modules for mechanical and electrical works, and the use of mechanical aids to lift them, significantly reduced the risk of manual handling injury. This enabled employees to maintain an improved posture when connecting and testing the units. Other benefits were found in the study including a considerable saving in time, no storage space required, no full floor scaffold required and improved consistency and quality of work.

4.3.1.2 Space issues

The availability of space on construction sites has a direct influence on workers safety and productivity. According to Winch and North (2006), it is known that congestion on site reduces output and generates hazards. Akinci et al. (2002) report that construction activities require a set of work spaces to be executed safely and productively. Akinci et al. (2002a) also find that to provide a safe and productive environment, managers need to plan for the work required by construction activities. Guo (2002) reported that a crowded jobsite is a major cause of productivity decrease and schedule interference or delay. Guo found that numerous workers, equipment, material, temporary facilities and permanent structures share limited space during construction. Space constraints thus affect the moving path and productivity, it is essential therefore to organise the available space efficiently in order to minimise space conflicts.

4.3.1.3 Crew relationship issues

M&E installations are complex (defined by the number of components or activities that interact), comprising many actions and activities by different trades or subcycles to be completed successfully (i.e. ductwork, pipework, electrical systems, data systems, with building fabric systems such as partitioning and ceilings etc.). Howell et al. (1993) describe that productivity suffers when the output of one subcycle delays a following step or when resources required for one subcycle are engaged in another subcycle. Thomas et al. (2004) report that symbiotic crew relationships occur when the pace of a crew depends on the pace of a preceding crew; that sometimes these relationships are loose and relatively independent and at other times these relationships are tight and closely dependant. The research found that it is more common to have tight relationships in mechanical, electrical, plumbing and finishing trades. It defines this tight and dependant relationship as symbiotic. It found that the performance of crews with symbiotic relationships is shown to be consistently worse than when these relationships are not present. A method to avoid symbiotic relationships is recommended by simplifying the operations using preassemblies. This reduces the amount of work on site by fabricating and assembling M&E modules offsite and simply installing these with a small installation team**.** Horman et al. (2006) reported on factors that bear significantly on the performance of electrical contractors in building construction projects. It found that when project work sequences are poorly planned, or poorly executed, electrical constructors often must contend with compressed schedules, trade stacking and out of sequence work.

4.3.1.4 Productivity issues

According to Hawkins (1997) labour costs typically constitute 30% of the overall project M&E costs, so maximising the output on site is essential to increase a contractor's performance and the value for money investment of the customer. This statement was part of a report of an investigative study undertaken by the Building Services Research and Information Association (BSRIA), and sets a foundation for understanding the problems and issues that the UK M&E industry faces within the construction sector. BSRIA undertook this investigative study comparing four UK, one American, one German and one Swedish construction projects to highlight productivity problems relating to M&E building services, to assist the UK M&E industry in promoting improvements in productivity, and to suggest remedies to solve these problems and improve performance. The study focussed upon activities specific to the onsite works, the aim of which was to divide output into its productive and non-productive components and then to develop best practice guidelines relating to input that would maximise the productive time and subsequent productivity achieved at the workplace. Significantly the UK projects monitored, had an average overall productivity of only 37%[13] when compared to observed best practice and an average task productivity of only 56% by comparison. The 37% is calculated by averaging results taken across the four UK projects monitored which measured overall productivity for ductwork, hot and chilled water pipework and cable management systems (also known as cable containment). Table 4.1 shows how the overall average productivity is derived from the calculated overall productivity figures for the UK projects monitored (from Hawkins 1997).

Table 4.1 BSRIA overall average productivity calculation

Project	Ductwork	Pipework	Containment	Average
A	40%	28%	32%	33%
B	34%	45%	42%	40%
C	24%	52%	42%	39%
D	28%	52%	30%	37%
			Overall average	**37%**

Hawkins found poorly conceived site parts storage and handling strategies which caused delays, with the very poorly performing projects being characterised by very poor levels of housekeeping. Workers were engaged in too much site cutting, drilling and assembly work and elevation of parts into final position. Remedies are suggested in the form of best practice recommendations but actual design and implementation of these remains at the discretion of the contractor[14]. Hawkins cites a total of 63 best practice recommendations across a project's pre-construction phase (including contract strategy; project planning; project organisation; temporary works; services design; construction philosophy and procurement strategy) and

13 The definition of productivity is described in Hawkins (1997), as is the method of calculation of overall and task productivity. The method of calculating overall productivity is also shown in the results section of this chapter.

14 The BSRIA recommendations describe the 'what' (to do), but not the 'how' (to do it). This Construction System provides the 'how to do it'.

construction phase (including work arrangement; work area control and installation). As described, this research project takes particular cognisance of these recommendations which are shown in appendix F of this thesis together with a statement of whether or not each of these are already implemented within CHt or if they have been implemented as part of the Construction System.

The report, “Innovative M&E Installation” by Wilson (2000), follows on from Hawkins (1997) and recommends that alternative systems, components, materials and innovative methods should be thoroughly evaluated to identify opportunities for productivity gains on M&E projects. It concludes that the UK (M&E) construction industry must replace outdated components and processes if it is to remain competitive in a global marketplace. This research found that the UK construction industry can realise a significant gain in installation performance through the adoption of innovative components and systems. Subsequent research conducted by BSRIA (Hawkins 2002) concluded that UK construction project teams that implemented improvement strategies and actions, in accordance with the BSRIA best practice recommendations, have realised significant improvements in site productivity. The research found the teams that designed for high site productivity, used innovative components and exploited offsite manufacture, realised a step-change improvement in construction site productivity rates. It also found that whilst the use of innovative products and offsite manufacturing techniques can deliver a huge improvement in project performance, their true value was still not being fully exploited.

It is the opinion of the author that the condition of productivity in UK M&E construction is by and large as Hawkins reported in 1997. Moreover, companies that do implement best practice do see improvement in productivity rates as Hawkins (2002) further reports. This is evidenced by the observations and research undertaken by the author during the course of this research project and described in this thesis. In fact, Court et al. (2005) describe how the increased cost of labour, on recently completed major projects, had a severe negative impact on the financial outcome of those projects and because of the scale of the cost overruns, CHt itself. To support these findings, Hanna et al. (2002) reports that electrical and mechanical constructions are high-risk industries due to low profit margins and a high labour component, and due to the high cost of labour and these low profit margins labour cost control is a very important function for profitability in these industries. Productivity and therefore labour cost was considered by the author to be the biggest single variable that can influence a projects financial performance.

4.3.1.5 Worker availability and skills issues

In a research project looking into barriers and opportunities for offsite manufacture in the UK by Goodier and Gibb (2005), it is reported that the UK construction industry has a historically low level of training when compared with other industries, and it is estimated that between 70 and 80% of the workforce in construction in the UK has no formal qualifications. Also a large proportion of the workforce are labourers, many of them self-employed, their skill base is narrow and their training is limited. It found also that there is an estimated annual turnover of between 65,000 and 75,000 people per annum in the industry. Significantly, the research found that electricians, joiners and bricklayers were the three skills generally cited the most, by all the sectors questioned, as being in short supply and contributing to the increased demand for offsite products.

4.3.2 Observational studies undertaken

Using the site first principle, and in order to commence the process of deciding where and how to start making changes to current practice, observational studies were undertaken on various sites of CHt and other companies. This included a range of sizes of projects in the UK (and one in the USA) across a number of industry sectors, and these were:

- A small custodial project (health facility inside an existing prison) in Edinburgh, Scotland;
- A large banking project (world headquarters facility) near Edinburgh, Scotland;
- A football stadium in the West Midlands, England;
- A medical research facility in Cambridge, England;
- A large hospital project in Oxford, England;
- A racecourse grandstand near London, England;
- A medium hospital project in Birmingham, England;
- A large hospital project in Portsmouth, England;
- A small office development in Birmingham, England;
- A healthcare refurbishment project in Los Angeles, USA;
- Random observations in various locations that caught the eye of the author.

A primary finding from these studies was that making-do, or improvisation[15] occurs naturally to a greater or lesser degree with regard to how physical work on site is carried out and this seemed to have a direct influence on productivity itself. Worksites were congested with materials and rubbish (figure 4.1); workers were involved in too much manual handling (figure 4.2); various trades had to work in the same space at the same time (figure 4.3); workers had to work on the floor (figure 4.4); and many other observations of bad practice, all evidencing the literature search findings. Also evident from these observations was that the worker wanted to have some sort of workplace to work in (or on), such as something as

[15] Improvisation is proposed here as a form of making-do. Making-do, according to Koskela (2004a), is the eighth category of waste adding to the 7 wastes defined by Womack and Jones (1996).

simple and basic as a workbench. There was no evidence found that this was provided for them and as such workers made their own. This improvisation ranged from very good (figure 4.5), to very poor (figures 4.6, 4.7) and to the downright dangerous (figure 4.8). It just seemed to be business as usual and led the author to conclude that unless direct interventions were made deliberately then things would not change.

4.3.3 Ethnographic study undertaken

In order to formulate an understanding of these findings in the context of this case study an ethnographic study was then undertaken. The purpose of this study was for the author to become a participant in the site process in order to be immersed in the day-to-day site activities and not just be an observer. Rather, the primary objective was to experience the conditions that exist on site and occur naturally, and how workers do their work without intervention. This method allowed the author to understand people's actions and their experiences of the world in natural settings as they occur independently of experimental manipulation (Cassell and Symon. 2004). One week was spent as a ductwork fitter's assistant (not a CHt project), and another week was spent as an electrician's assistant (on a CHt project). This involved the author doing actual installation work with teams under the direction of the team leader. A diary was kept at the end of each day to record events and discussions and digital images were taken.

4.3.3.1 Rich picture of ethnographic findings

A rich picture of the key words and phrases from the diary entries was created in order to reveal a rich moving pageant of relationships which is a better means of recording relationships and connections than is linear prose (Checkland and Scholes 1992). The key words and phrases from the daily diaries were mapped around six of the seven wastes.

Figure 4.1 Congested work site

Figure 4.2 Manual handling onto a scaffold

Figure 4.3 Various trades in the same workplace

Figure 4.4 Working on the floor

Figure 4.5 Improvised workbench

Figure 4.6 Congested and improvised workplace

Figure 4.7 Improvised workplace

Figure 4.8 Improvised workbench

The seventh not considered relevant in the context of this mapping was “goods and services which don’t meet the needs of the customer”. However making-do was added, plus physical and psychological issues, these being two of the themes being investigated during this particular study. The rich picture is presented in figure 4.9.

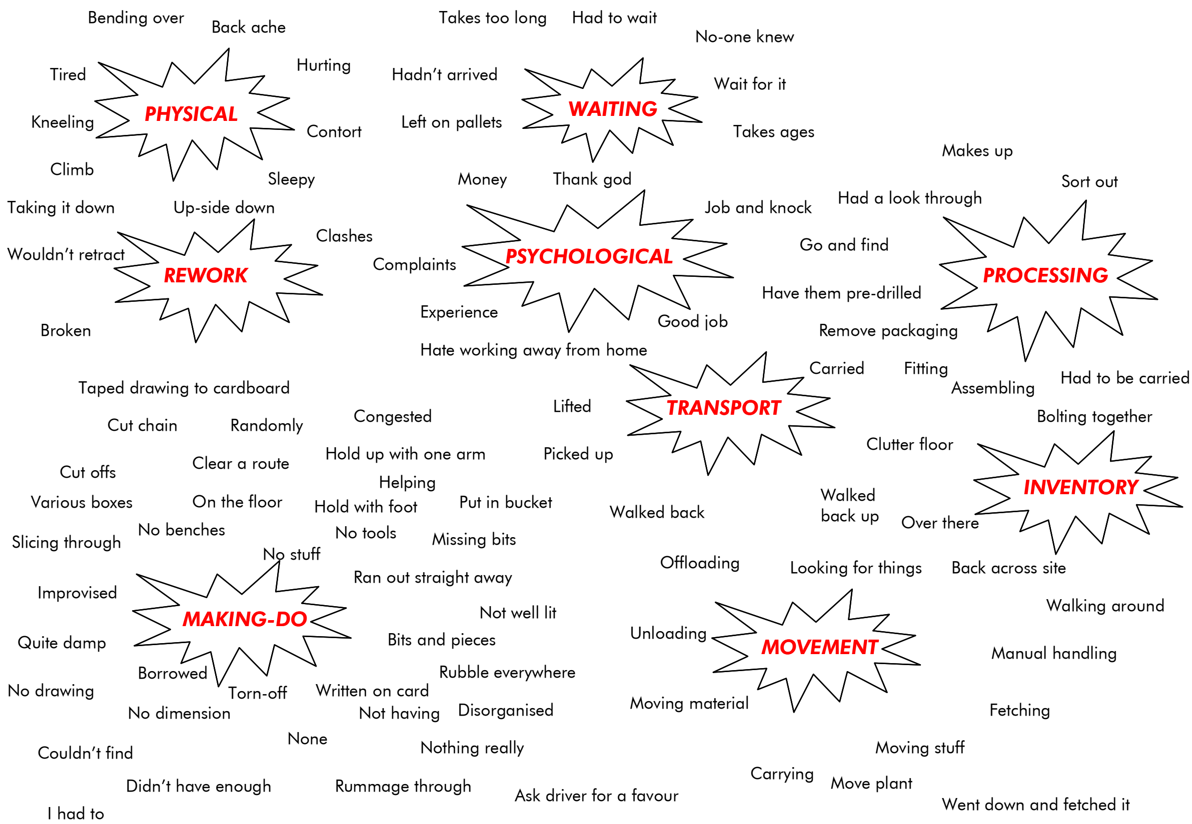

Figure 4.9 Rich picture of the key words and phrases from the ethnographic study

As can be seen from this rich picture the findings from the ethnographic study fell into the seven categories of waste (including Koskela’s making-do) and confirmed to the author the findings from the observational studies described earlier. The main findings from this study are summarised as follows:

- Process waste was prolific on the construction sites observed during these studies;
- There was limited, unplanned or improvised workplace organisation, workbenches, and equipment;

- Assembly work was carried out on the floor or on whatever came to hand;
- There was nowhere to hang drawings or other information;
- Materials were stored randomly around the site in no particular order, in unknown quantities and having to fetch them yourself;
- Scaffold systems were provided that had to be accessed by climbing a ladder and opening flaps, with no facilities to store materials or tools. If something was missing, the worker had to climb back down to get whatever was needed;
- Tools were only provided by the tradesmen themselves; they had what they had irrespective of their suitability;
- Various trades worked in the same area at the same time. Materials for one trade were left in the way of other trade / trades.

Significantly the author experienced the conditions on site without intervention and the physical discomfort felt as a result[16].

4.3.4 Pilot experimental study

At this point in the research process a pilot experimental study was devised to test interventions designed to overcome the issues found in the literature search, and those observed and experienced in the ethnographic studies. This is described in Court et al. (2005); this being the first paper submitted for this research project and is contained in appendix A. This paper (paper 1) was presented at the IGLC 13 conference in Sydney, Australia in July 2005, in the Championship: Theory. In this study trial Lean interventions were made on a live project of the company which had positive results. These interventions

[16] This includes physical back pain from bending, working on the floor and climbing up and down scaffolds and ladders.

were the first stage of designing and implementing the Construction System and the findings from this study were used to inform and develop the System further.

4.3.5 Summary of step 2

The issues found during the literature search, observational and ethnographic studies are summarised in table 4.2. Each of these findings show that work undertaken in a traditional manner (or without deliberate intervention to eliminate the cause of it) is either potentially harming the worker or is a form of waste (in Womack and Jones terms), making-do (Koskela 2004) and improvisation (Court et al. 2005) all leading to poor productivity. Collectively these research findings informed the author what needed to be done, which was to:

- Avoid congestion on site in order to improve workers output and avoid creating hazards;
- Use methods to avoid relationships between subcycles and work crews that exist and delay and interfere with each other;
- Improve construction workers occupational health as well as their safety by providing good ergonomics, appropriate working tools and a good working environment;
- Exploit the use of prefabricated modules and use mechanical aids to lift them, thereby improving workers posture carrying out simpler assembly tasks;
- Use innovative components and systems to replace outdated components and processes;
- Supply the right parts to the right place and at the right time to avoid poorly conceived materials handling strategies leading to poor site productivity;
- Avoid poor workplace management (housekeeping and tidiness);
- Avoid designing work that uses site workers that are in short supply or inappropriately skilled.

Table 4.2 Summary of primary issues

Primary issues	Source
Manual handling injuries caused by repetitive and heavy lifting; bending and twisting; repeating actions too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment and psychosocial factors.	The Health and Safety Executive (2007a, 2007b); ethnographic study.
Slow accidents caused by health factors.	Gibb (2006).
Site congestion generates hazards and reduces output.	Winch and North (2006), Akinci et al. (2002, 2002a), Guo (2002), observational studies, ethnography.
Subcycles and crew relationships delay each other.	Howell et al. (1993), Thomas et al. (2004).
Too much site cutting and elevation of parts into position.	Hawkins (1997), observational studies, ethnography.
Poorly conceived materials handling strategies.	Hawkins (1997), observational studies, ethnography.
Very poor levels of housekeeping.	Hawkins (1997), observational studies, ethnography.
Site workers in short supply or inappropriately skilled.	Goodier and Gibb (2005).
Limited, unplanned or improvised workplace organisation, workbenches, and equipment.	Observational studies, ethnography.
Assembly work carried out on the floor or on whatever came to hand.	Observational studies, ethnography.
Nowhere to hang drawings or other information.	Observational studies, ethnography.
Scaffold systems provided that had to be accessed by climbing a ladder and opening flaps, with no facilities to store materials or tools.	Observational studies, ethnography.
Tools only provided by the tradesmen themselves - they had what they had irrespective of their suitability.	Observational studies, ethnography.

These research findings for the current state allowed a basis of understanding to commence the next step in the research process which was data collection for the future state (the vision of how things could be).

4.4 STEP 3: DATA COLLECTION FOR THE FUTURE STATE

This step in the research process involved data collection for the future state and continued the action research method. It included a literature search for the future vision, looking inside and outside the industry for best practice and innovation using observational studies. This step in the research process began with a taught module at Loughborough University; Lean and Agile Manufacture (Module 04MMP203), which was the turning point for the author in understanding manufacturing methods in use today. Understanding these efficient methods and systems used in manufacturing provided a firm foundation and framework for being able to implement leading edge manufacturing techniques into the construction industry. The elements of the taught module were:

- Lean and agile manufacturing;
- Production planning and control in lean systems;
- The cellular business (the effect of lean and agile);
- Issues with lean manufacture;
- Period batch control and inventory management;
- Optimised production technology;
- Theory of constraints; real time scheduling and demand management;
- Postponement strategies.

Following the learning from this module, manufacturing was seen as a rich source of efficient techniques and methods for possible adoption into construction. The primary manufacturing methods therefore further researched were: Lean and agile manufacturing with postponement; modular assembly; reflective manufacture; period flow control; ABC parts classification and vehicle assembly. Ergonomics[17] was also included because of its importance to manufacturing workplace design.

4.4.1 Literature search

4.4.1.1 Lean and agile manufacturing with postponement

Techniques in Lean tend to suit the highly efficient producer, particularly the production of high variety commodity items at minimum cost. Lean is efficient but can it also be responsive? Lean seems to be much more appropriate for efficiency and cost cutting, whereas agility is the ability to rapidly reconfigure the production system (and the supply and distribution systems) to meet new product requirements. Agility has a responsiveness dimension which does not seem to be part of the Lean definition. It is possible to link different sorts of systems together using the concept of the decoupling point, for example the Lean factory can be separated from the agile distribution chain by means of a decoupling store. The factory produces modules that are placed in the store and as the demand changes the modules can be quickly assembled in the distribution chain to provide the customer with a unique offering. If the decoupler is moved very close to the customer so that it is far downstream and the module store is close to the retailer then you have a form postponement strategy where there is the means to rapidly assemble the product to meet the precise customer order. If the distribution of the product is delayed to the last minute and only configured and distributed when the customer order is received then you have logistics postponement (Yang and Burns 2003). According to Mason-Jones et al. (2000), Lean and agile paradigms, though

[17] Whilst ergonomics is not a manufacturing method itself, vehicle assembly according to Granath (1998) requires good ergonomics, this being the reason for review here.

distinctly different, can be and have been combined within successfully designed and operated supply chains (this is known as Leagility). Naylor et al. (1999), define Leagility as:

"…the combination of the Lean and agile paradigm within a total supply chain strategy by positioning the decoupling point so as best to suit the need for responding to a volatile demand downstream yet providing level scheduling upstream from the decoupling point."

Postponement therefore is an approach then that helps deliver more responsive supply chains. Form postponement which involves the delay of final manufacturing until a customer order is received is commonly regarded as an approach to mass customisation (Skipworth and Harrison 2004). Mass customisation is providing numerous customer chosen variations on every order with little lead-time and cost penalty. Skipworth and Harrison proposed the application of form postponement as a solution to deal with the high demand uncertainty resulting from the provision of many variants whilst ensuring low operational costs are maintained with short reliable lead times. Examples of how product architecture enables postponement are given in Ulrich and Eppinger (2004). They link the product architectural choices to platform planning, this being the collection of assets including component designs shared by products.

4.4.1.2 Modular assembly

According to Fredriksson (2006), modularity is a design strategy that is used by companies producing such different products as aircraft, household appliances, trucks and cars, computers and software. The popularity of the concept he describes is explained by its appealing logic, which is to divide a complex system into decoupled and manageable modules that are easily put together into a working whole. A definition of this is given as:

"...the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks".

Modularity in production thus implies a dispersed assembly system in which some activities are pre-assembly (of components into modules) and other activities are final assembly (of components and modules into end-products).

4.4.1.3 Reflective manufacture and quality of work

Reflective manufacture is an important socio-technical approach to manufacture that arose in Sweden at the Volvo Uddevalla plant. Its evolution is described by Granath (1998) and is regarded in Sweden as a person centred approach to automobile assembly although it was never fully developed. It is now attracting more attention with the development of mass customisation strategies. Reflective systems do vary in the way that they are designed, however they tend to suit a highly modularised product. The research found that Volvo, when looking into the development of production systems, looked into quality of work as well as efficiency of production. According to Granath, quality of work contains a number of aspects; he suggests that a system that offers professional meaningful work is better than those that only offer unskilled or semi-skilled work. The aspects that signify professional work are control over methods, time and quality plus the responsibility to plan ahead and the knowledge needed to reflect on work done. Quality of work also requires good ergonomics, appropriate working tools and a good working environment.

A typical form of reflective system generally has module build units or cells, each the responsibility of a semi-autonomous team. Team members are multi-skilled and highly trained so that they are interchangeable. There are likely to be standard operating procedures

(SOP's) but members themselves generally design these. In these systems there is often a significant materials acquisition unit with a kitting function and the system operates using a pulse-system or period batch control. Period batch control (also know as period flow control) is a Just-In-Time, flow control, single cycle, production control method based on a series of short standard periods generally of one week or less (Burbidge 1996). Alternatively the system operates using ABC parts classification.

4.4.1.4 ABC parts classification

According to Hopp and Spearman (2001), in most manufacturing systems a small fraction of the purchased parts represent a large fraction of purchasing expenditures, so management should therefore focus most attention on these parts. To accomplish this, ABC classification is used by many manufacturing firms for categorising and managing purchased parts and materials. Parts have been classified by Hopp and Spearman as follows:

A parts The first 5 to 10 percent of the parts accounting for 75 to 80 percent of expenditure;

B parts The next 10 to 15 percent of the parts accounting for 10 to 15 percent of expenditure;

C parts The bottom 80 percent or so of the parts accounting for only 10 percent or so of expenditure.

It makes sense therefore to use appropriate methods to tightly coordinate the arrival of A parts. The cost of holding small excess quantities of C parts is not large therefore such methods would not be required for these. B parts are in between so they deserve more attention than C parts, but less than A parts. The main point of this is that inventories of different classes of parts should be treated differently. As stated, type A parts are expensive and bulky, for which stockholding is costly (and a waste in Lean terms – the waste of inventory). The way to therefore manage these expensive parts (according to Hopp and Spearman), is to keep levels to an absolute minimum which is precisely the idea behind Just-In-Time (JIT). For these reasons the ABC method was adopted for use because of its high degree of suitability and applicability to the Construction System (and is a component classification method used in reflective manufacture). No other method was therefore considered.

4.4.1.5 Ergonomics

Ergonomics is a theme that the author sought to understand to be able to design work cells that were suitable for the worker carrying out their designated work. It is a science devoted to determining the range of anatomical, physiological and psychological human factors and designing work environments conducive to these ranges with the objective of maximising productivity and minimising injury (McNamara, 1986).

According to the Health and Safety Executive, in their publication "Understanding Ergonomics at Work" (HSE 2003), ergonomics is a science concerned with the 'fit' between people and their work. It puts people first taking account of their capabilities and limitations. Ergonomics aims to make sure that tasks, equipment, information and the environment suit each worker. By assessing the relevant aspects of people, their jobs, equipment, the working environment and the interaction between them, ergonomists are able to design safe, effective and productive work systems.

To date most of the literature reviewed relating to ergonomics in construction reveals research in the health and safety field covering:

- Health and Safety in construction generally (Koningsveld and Van Der Molen 1997, HSE 2007);
- Manual handling (Sillanpaa et al. 1999, HSE 2000);
- Working posture (Abdelhamid and Everett 1999, Kivi and Mattila 1991, Sporrong et al. 1999);
- Overexertion (Everett 1999);
- Musculoskeletal disorders (HSE 2007a, 2007b).

Of particular relevance to this research project are the findings in Sillanpaa et al. (1999). This research found that by using auxiliary handling devices (wheels, lifting straps and workbenches) significant reduction in the muscular load on the workers being tested was experienced when compared to conventional work methods (manual lifting and working bent over on the floor). It was not the intention of this research project to conduct more studies into these factors but to be able to take due cognisance of them. The aim was to be able to design safer, more effective and productive workplaces and systems for M&E workers that considered the basics of ergonomics. This also meant designing work to fit the worker[18] and not fitting the worker to the work (Bridger 2003). A key learning point for the author was that if you approach the design of work from an ergonomic perspective two things happen as a natural by-product: work becomes safer for the worker and the worker becomes more productive. This is because work itself is designed to be safer, more effective and productive.

[18] Bridger (2003) uses the phrases "fitting the job to the man (FJM)" and "fitting the man to the job (FMJ)". The author prefers to use the phrases "designing work to fit the worker" and "fitting the worker to the work".

4.4.2 Observational studies

A further observational study was undertaken in order to formulate an understanding of manufacturing methods in the context of this research. This study was conducted at the BMW "Mini" factory in Cowley, UK. This was to observe the assembly of car bodies and the final car assembly process. This was to give the author a feel for a manufacturing and assembly environment and how people worked. Importantly, the author, by observing the various assembly processes conducted either by robots or people, was able to get many visual clues as to how the methods could be transferred to M&E construction. These visual clues included (most significant):

- A logistics team delivering components trackside, directly to point of use and Just-In-Time;
- Conveyors delivering modules (engines, dashboards etc.) exactly on time when the particular car body arrived at the assembly station;
- No manual handling by assembly workers other than small parts;
- Work cells with everything to hand. Workers were allowed some discretion in organising their own assembly / work cell;
- Car bodies rotating so that components could be fitted to the bottom of the car without the need for the worker to do this from below;
- Simple assembly processes to build a complex product – modular assembly;
- Precise timing of vehicle arriving at workstation, with work cells, components, everything synchronised perfectly;
- Clean and tidy workplace, no mess, minimum inventories required;
- Visual management aids;

- Senior managers spending one week per year in each plant on the factory floor doing actual work. A financial manager was witnessed loading sheet steel onto a conveyor ready for processing.

Photographs were not allowed during the factory visit so these visual clues served as a reminder of what could be possible and set a foundation for thinking about these methods being applicable and transferable to M&E construction.

4.4.3 Summary of step 3

Taken together, these collective research findings formed the underpinning techniques and methods used for the design of the Construction System to specifically address the research problem with appropriate countermeasures. This set the platform for the next step in the research process, breakthrough thinking for development of options for analysis.

4.5 STEP 4: BREAKTHROUGH THINKING FOR DEVELOPMENT OF OPTIONS FOR ANALYSIS

The next step in the research process was to bring together the learning in the previous steps in order to facilitate what was termed as breakthrough thinking for development of options for analysis, however ideas became apparent and developed as the learning progressed through the previous research steps. The ideas were bought together when thinking through each of the research findings and the manufacturing methods that could be used to countermeasure the research problem. The thinking culminated in the development of the conceptual Construction System model which is the subject of the second paper submitted for the Engineering Doctorate and is described in Court et al. (2006) and is contained in appendix B.

This paper (paper 2) was presented at the IGLC 14 conference, Santiago, Chile in July 2006, in the Championship: Production System Design.

4.5.1 The Construction System

The Construction System is presented in figure 4.10 and its underpinning theory incorporates manufacturing techniques and methods such as Lean and agile manufacturing with postponement, modular assembly, reflective manufacture, ABC parts classification and pulse-driven scheduling.

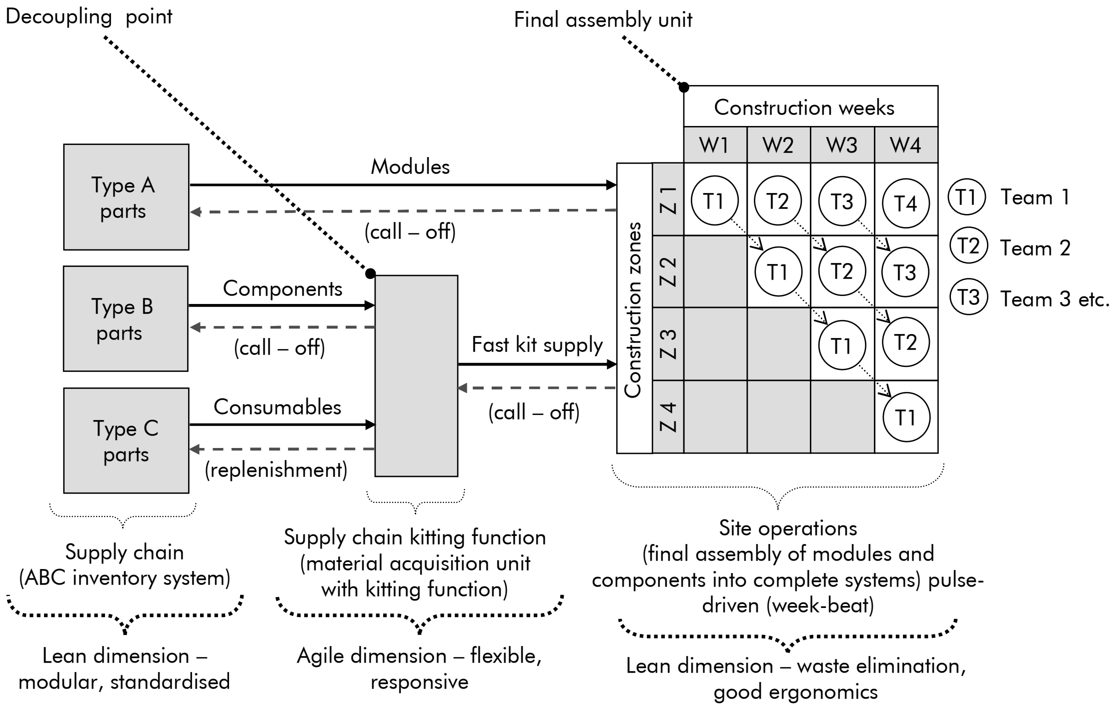

Figure 4.10 Model of the Construction System (adapted from Court et al. 2009)

In this model, the supply chain is categorised using ABC parts classification with modules (category A) being delivered to site on a call-off system. Components (category B) are parts kitted for delivery to site via a postponement function (operated in the supply chain). Consumables (category C) are low value, high quantity materials constantly available supplied by a kanban[19] replenishment system. Site operations are conducted by semi-autonomous trade teams (T1, T2 etc), using mobile work cells and ergonomic access equipment (Court et al. 2005) specifically designed for their activity. The System operates using a pulse-driven which has been called the Week-Beat (this is the Systems takt[20] time), the pulse rate or takt time being one week.

The supply chain element of the Construction System provides the Lean dimension, this being modular and standardised. M&E distribution systems are pre-combined into modules (type A parts) and these modules are to be assembled off-line (at CHt's and other suppliers manufacturing centres) and then brought onto the main assembly line (the construction site – the final assembly unit) and incorporated through a small and simple series of tasks (in each construction zone and plantroom).

The postponement function (the decoupling point) provides agility in that each trade team (the customer – the next person or step in the process, Liker 2004) gets exactly what they want, when they want it and where they want it, delivered to point of use by a logistics team. This postponement function is to be carried out in the supply chain and is not a physical place in its own right. The site operations component (final assembly unit) provides a further Lean dimension with methods that eliminate process waste (muda). All teams are to be provided with good ergonomics, appropriate working tools and a good working environment (Granath 1998) in the form of specifically designed mobile work cells suitable for their specific tasks. These Lean and agile attributes are designed to standardise the work, process and products to

19 A kanban is a signal that gives authorisation and instructions in a pull system (the Lean Enterprise Institute 2003).

20 Takt time is a German word for a pace or a beat, often liked to a conductor's baton. Takt time is a reference number that is used to help match the rate of production in a pacemaker process to the rate of sales (Rother and Harris 2001).

create flow, pull and value delivery. The ergonomic and workplace organisation attributes are to be designed to specifically improve workers health, safety and productive output (Court et al. 2005).

The System operates using a pulse-driven system which has been called the Week-Beat (the pulse rate is one week). Here each team is to have one week in each construction zone (approximately 1,000 square meters) to complete its work before moving to the next zone and so on. The next team, T2, follows on at the Week-Beat interval and the next team follows similarly. The Week-Beat method described here is specifically aimed at ensuring that no two or more trades work in the same place at the same time unless allowed to do so (when still separated by physical space). This will prevent subcycles or crews interfering with each others progress and to provide an uninterrupted flow of work in their own clear space. The beat of the System is one week because this period matches the quantity of work to be done by an optimum amount of workers in that space. For instance each construction zone has approximately 450 metres of ventilation ductwork to be fitted. One pair of workers can fit 22.5 metres of ductwork per day (higher productivity rate allowed – usually 17.5 metres per pair per day), therefore when allowing four days to do this work (with one day safety buffer), five pairs of workers are required. With all their equipment and materials, 10 workers are about on the limit for the space capacity within a 1,000 square metre construction zone. Where longer periods are required for other trades to carry out their work in this sized space, such as partitioning work[21], then this is treated as a bottleneck in the System and how it is managed is described later in this chapter. Another Lean feature of the Construction System which to be deployed is the Last Planner System (LPS) of production control which is also described later.

[21] Also known as dry-lining.

4.5.2 Summary of step 4

This section has described the design of the Construction System which is as a set of specific countermeasures to overcome the problems that exist in construction as discussed previously. These primary issues together with the Construction System components, which act as the countermeasures to them, are presented in table 4.3.

4.6 STEP 5: ANALYSIS AND EXPERIMENTATION OF OPTIONS FOR IMPLEMENTATION

This step in the research process describes the details and plans being made, at that time, to prepare the working details of the Construction System into real and meaningful methods ready for implementation in the near future. It was about turning theory into practice but, as Project Leader, the author had the responsibility to CHt to ensure that any methods devised would fit into the then existing company procedures and policies that govern the way CHt conducts itself and its live projects. CHt has quality management and Health and Safety systems and procedures (and others) that are part of its business governance so that any new methods devised as part of the design of the System had to be complimentary to these procedures. In addition, this had to be done in conjunction with the case study project team, who had project delivery responsibilities as their day job (as did the author), so any development of the System, with this team, had to ensure that the actual live project objectives were still being achieved. The process of selecting and testing options for their suitability for implementation was done against a set of principles, parameters and ground rules set which are described later in this section. The first task was the selection of the case study project itself and to gain full support from the Business Leaders of CHt. This was done using a narrow and deep approach to implementation.

Table 4.3 Primary issues and countermeasures

Primary issues	Construction System countermeasures
Manual handling injuries caused by repetitive and heavy lifting; bending and twisting; repeating actions too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment and psychosocial factors.	Modular assembly with mechanical lifting aids; trained manual handlers in logistics team; materials in purpose made stillages, trolleys and roll-cages.
Slow accidents caused by health factors. The period over which the incident occurs may be longer but the result is the same, a worker gets injured but it takes longer.	Modular assembly; ergonomic workplace design.
Site congestion generates hazards and reduces output.	Week-Beat (trade separation); mobile work cells; materials in mobile carriers.
Symbiotic crew relationships delay each other. These are tight and closely dependant trades and these are more common in mechanical, electrical, plumbing and finishing trades.	Week-Beat (trade separation).
Poorly conceived materials handling strategies.	ABC parts classification; modular assembly; Just-In-Time parts kitting.
Very poor levels of housekeeping.	Physical waste managed by trained logistics team.
Too much site cutting, drilling, assembly work and elevation of parts into position.	Modular assembly with mechanical lifting aids.
Outdated components and processes.	ABC parts classification; push-fit components; the Construction System; Last Planner System.
Site workers in short supply or inappropriately skilled.	Fewer workers required (modular offsite assembly); lower skill mix needed for simpler assembly tasks.
Limited, unplanned or improvised workplace organisation, workbenches, and equipment.	Workplace organisation; mobile work cells.
Assembly work carried out on the floor or on whatever came to hand.	Workplace organisation; mobile work cells.
Nowhere to hang drawings or other information.	Workplace organisation; mobile work cells; complete with mobile drawing boards.
Scaffold systems provided that had to be accessed by climbing a ladder and opening flaps, with no facilities to store materials or tools.	Ergonomic workplace design; walk-up scaffold systems; scissor lifts.
Tools only provided by the tradesmen - they had what they had irrespective of their suitability.	Appropriate working tools provided for all tradesmen.

4.6.1 Narrow and deep approach to implementation

When thinking through the future implementation of the System, and to gain maximum support from CHt Business Leaders, a narrow and deep approach for a case study project was agreed with the Industrial Supervisor, the Business Leader for CHt. This method was presented at the International Group for Lean Construction, IGLC 14 - Santiago, Chile (Arbulu and Zabelle 2006). In this paper it is said that implementing Lean means an organisation transforms itself from a current state to a future state vision that incorporates a Lean ideal. They propose a strategy for organisations to increase the likelihood of success when going through a Lean transformation. The paper highlights five key elements for a successful implementation including vision, skills, incentives, resources and detailed action plans. Arbulu and Zabelle argue that adopting a shallow and wide transformation approach implies implementing transformation in more than one project at a time, and in their experience, has proved to be counterproductive resulting in a waste of time and money. This approach is presented in figure 4.11.

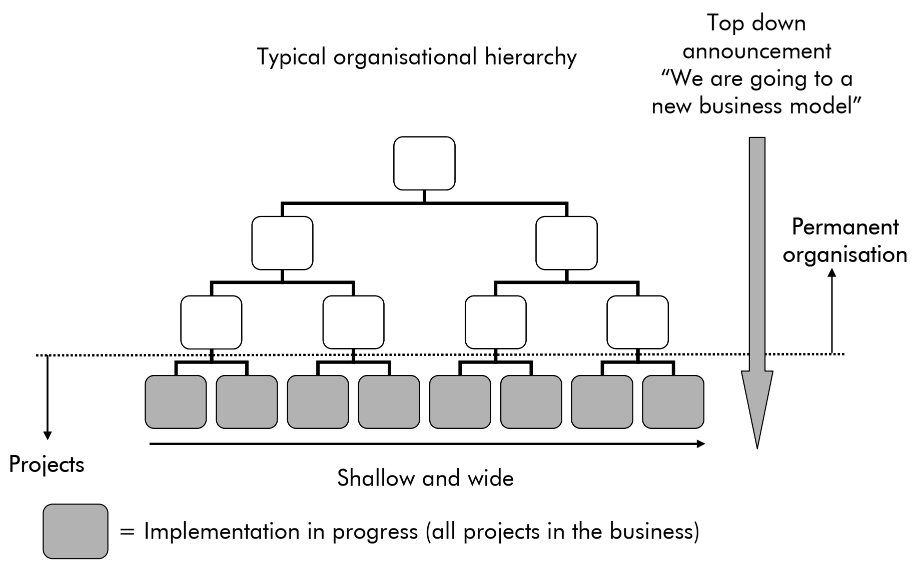

Figure 4.11 Shallow and wide approach, top down implementation (adapted from Arbulu and Zabelle 2006)

Arbulu and Zabelle recommend an alternative approach in their paper which is referred to as a narrow and deep approach, taking projects themselves as the basis for transformation as part of a business transformation process, which is presented in figure 4.12.

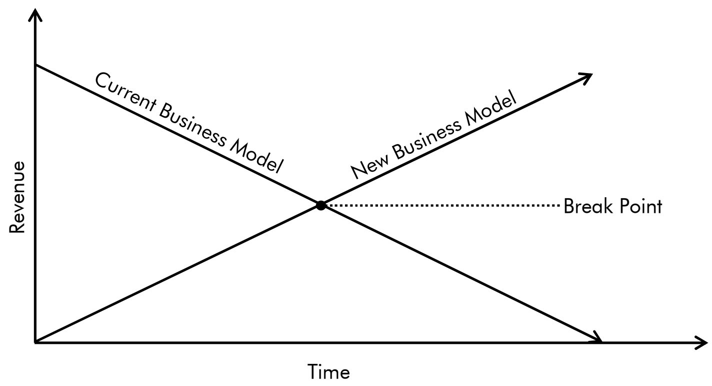

Figure 4.12 Business transformation process (adapted from Arbulu and Zabelle 2006)

The main benefits of adopting this approach include (from Arbulu and Zabelle 2006):

- "Maintain current operations while transformation occurs. The objective is a smooth transformation";
- "Better control of when the break point occurs. The break point is defined here as the moment where at least 50% of projects are being delivered through the new business model";
- "Better control of capability development. The adoption of the new business model imposes many technical challenges for leaders and project team members";
- "Better decision making regarding which project is next in the transformation process. For example companies may want to gain competitive advantage faster by selecting projects from key clients or industry sectors based on their contribution to the organisation's revenue";
- "The impact of top-down leadership support is higher thanks to working in a more controlled environment (e.g., one project instead of ten). A Lean transformation initiative requires significant time dedicated to lead teams through change".

Figure 4.13 presents a narrow and deep approach to Lean implementation with top down leadership support. This approach implies that the transformation process occurs from the bottom up, in other words from the projects themselves.

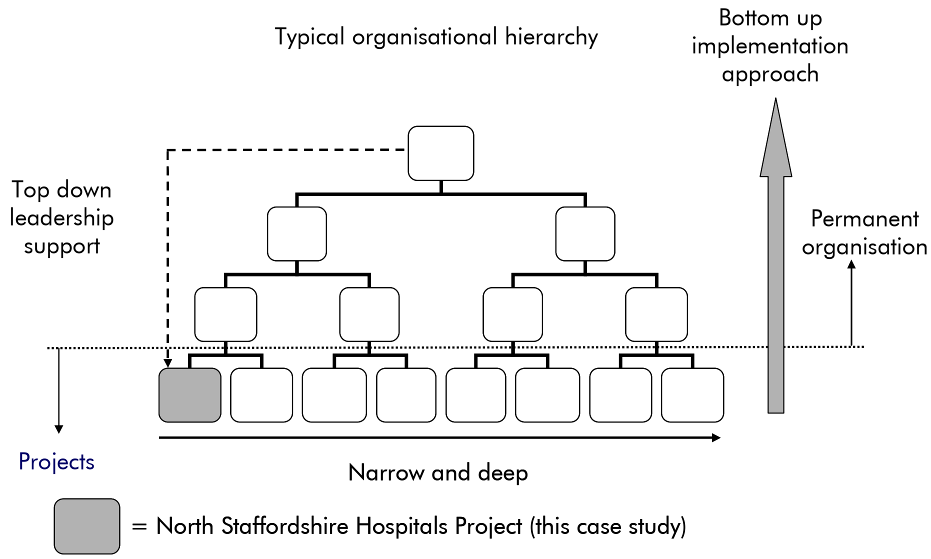

Figure 4.13 Narrow and deep approach, bottom up implementation (adapted from Arbulu and Zabelle 2006)

This was the method agreed for implementation on the case project with full top down leadership support from CHt. As Arbulu and Zabellle state, the construction industry has a key advantage compared with other industries regarding how to approach a sustainable Lean transformation and this advantage is having projects. These projects enable the design and implementation of temporary business systems and can be the basis for transformation, the means to create a new business model (figure 4.12). CHt has projects and a further advantage is that the thesis author is a Project Leader in the company and in particular the North Staffordshire Hospitals Project in Stoke-on-Trent, Staffordshire, UK. This project therefore became the subject of the narrow and deep approach and was the case study project where the Construction System was implemented and tested as part of this research project.

4.6.1.1 The case study project

The case study project is part of the development of a major acute hospital being procured using the UK Government's Private Finance Initiative (PFI). The project is to be developed in phases across two existing operational hospitals. The phases are a new Maternity and Oncology Centre (20,000 m² gross internal floor area); Sterile Services Department (2,000 m² gross internal floor area); Hub and Wards Unit (52,000 m² gross internal floor area); Diagnostic Treatment Centre (20,000 m² gross internal floor area) and the Haywood Hospital – remote location (12,000 m² gross internal floor area). The project commenced construction in December 2006 (M&E commenced August 2007) and is due for completion in 2012. The total value for the M&E work is £100 million. The major new-build phases of the project are presented in figure 4.14 (excluding the Haywood Hospital phase which is in a remote location five miles away from the main site).

Figure 4.14 Site layout showing major new-build phases of the project

The Construction System is being applied on each phase of the case study project the first being the new Maternity and Oncology Centre. This is a 20,000 m² building over four floors. It has electrical and water storage plantrooms in its basement, with main ventilation plantrooms over the Oncology Centre at level two and on the roof at level five. Riser shafts are located around the building and distribute air, water, medical gas, electricity and the like throughout the building to the various departments. Corridor ceiling voids distribute the services from the riser shafts and then further into individual rooms and spaces, again in the ceiling voids. Finally services distribute inside dry-lined walls to points of use such as electrical sockets, sinks, basins and bed-head units; everything you would expect to see in a new and modern healthcare facility.

4.6.1.2 Conditions for success

Arbulu and Zabelle (2006) outline five key elements that are required for successful implementation and state that these should be used as a checklist prior to commencing any implementation effort, and these are listed below.

1 **Vision** - "Without a vision stakeholders will be confused. Creating a vision sets the framework for the mission, objectives and strategies for the implementation effort at the project level".

2 **Skills** - "If skills are missing during any Lean transformation process, people will be anxious. This applies to project team members, top management, and anyone that plays a role in the implementation effort. Skills are instilled in the selected project team through training. Training is one of the most important aspects of managing change because it fills the gaps between the current business model and the new business model".

3 **Incentive** - "If an effective incentive scheme is missing, change will be gradual. The new systems and methods of working may eventually be adopted as project teams begin to see the benefits, but the change will most likely take longer than desired".

4 **Resources** - "If resources are insufficient, frustration will be the end result. It is critical to provide sufficient resource to support the implementation effort. Teams will need to be facilitated, individuals will need to be trained, and managers will need to be coached".

5 **Action Plan** - "If a solid action plan is not in place, the likely result will be a false start. In an effort to make progress, teams will start down one path of action without knowing if this is the right path…It is therefore essential to agree a plan of action for the implementation effort with Project Leadership".

They state that if one or more of the elements are not in place then the implementation effort will most likely fail. Table 4.4 outlines the probable outcome if one of the elements is missing. Using these elements as a checklist, each was worked through in order to plan the actual implementation and to ensure that all the elements for successful implementation were in place according to this method.

Table 4.4 Elements for successful implementation (adapted from Arbulu and Zabelle, 2006)

Result	Vision	Skill	Incentive	Resources	Action plan
Change	Yes	Yes	Yes	Yes	Yes
Confusion	***No***	Yes	Yes	Yes	Yes
Anxiety	Yes	***No***	Yes	Yes	Yes
Gradual change	Yes	Yes	***No***	Yes	Yes
Frustration	Yes	Yes	Yes	***No***	Yes
False start	Yes	Yes	Yes	Yes	***No***

4.6.1.2.1 The vision element for success

The vision element was straightforward as this was articulated by the Business Leaders of the group of companies which is presented in figure 1.1 contained in chapter 1 of this thesis, along with the safety vision. This is:

- To be Incident and Injury Free, returning everyone home safely after a productive days work;
- To be the company of first choice for all stakeholders - customers, employees, suppliers, trade contractors and the society in which we live;
- To challenge and change the poor image of construction worldwide;
- With Leanness and agility to adopt processes to compete with world-leading businesses.

This vision flowed straight through to the vision for the case study project, and further articulated in the stated aim for this research project described in chapter 2.

4.6.1.2.2 The skill element for success

Bringing the skill element to the project was the role of the thesis author who is the M&E Project Leader for CHt. In this role the new Lean and agile skills acquired in undertaking this research project to design the Construction System were directly fed into the case study project with training and familiarisation given to the project team members. The author also had the responsibility to set objectives for team members for their annual appraisal, and Lean development and implementation objectives were set as part of them.

4.6.1.2.3 The incentive element for success

To a certain extent, the responsibility to set these objectives may well have influenced the next element, the incentive. The annual appraisal scheme was directly linked to the payment of bonus (other conditions apply). So if team members excelled at learning and implementing Lean methods, and was reflected in their annual appraisal, this could directly lead to a financial reward. It is known that incentives are not purely financial and money is not a key motivating factor (despite popular belief) for most people (Maslow 1943) and that a prime incentive is recognition itself for a job well done. The team will be recognised once the Construction System is implemented, tested and proved successful as will the project itself.

4.6.1.2.4 The resources element for success

Resources are the next element. The project had the resources and these were the project team members themselves, recruited by the author from within and outside of CHt. Certain key team members have directly contributed to the core elements of the Construction System which is described in this thesis.

4.6.1.2.5 The action plan element for success

Finally the last element is the action plan. It is essential to co-create and agree an action plan for the implementation effort on the project. The Construction System has been under development in conjunction with team members from the case study project from the beginning of this research project, and its implementation is discussed in this thesis. The action plan was therefore this research project.

Having selected the case study project along with achieving CHt top management support, the next actions in this research step is to commence the process of turning the theory of the Construction System into practice.

4.6.2 Turning theory into practice

This section describes how the features of the Construction System were designed and made ready for implementation on the case study project. To visualise how this fits into the project figure 4.15 presents the project value chain (adapted from Porter 1985) and is shown with the Construction System features associated with the appropriate step in the value chain.

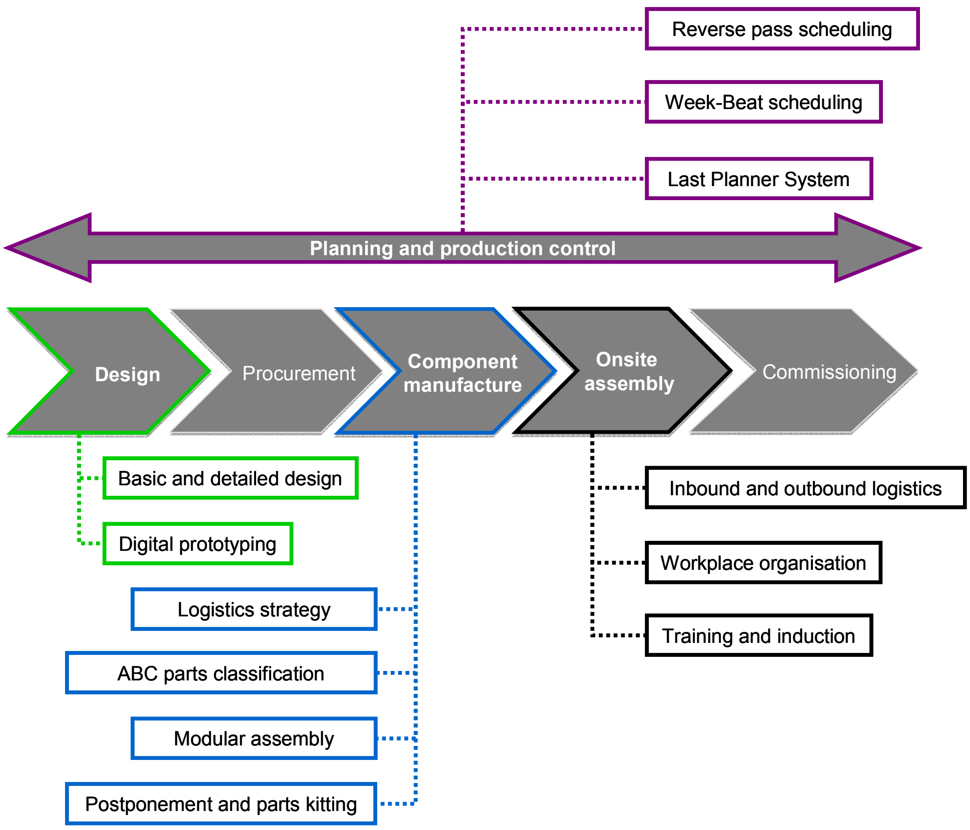

Figure 4.15 Project value chain with associated Construction System features

The value chain in figure 4.15 represents the series of activities that deliver the project from design though to commissioning and then handover to the client; this also allows identification of the all the steps[22] across the whole value stream of a project (Womack and Jones 1996). The Construction System developed relies on, and has to be complimentary to,

[22] There are processes and sub-processes within these value steps and these will be discussed later in this thesis.

the processes and procedures already in use within CHt, such as design and procurement. Whilst these are not the subject of this research project they are touched by it and are described in this chapter to allow the reader to understand the end to end project delivery process that the Construction System fits into.

The section begins with describing the use of cross functional teams who together designed these features with a set of guiding principles, parameters and ground rules to guide the team through the decision making processes undertaken. The remainder of this section describes each feature within the project value steps and how they act as countermeasures to the issues they are designed to overcome. The section concludes with a description of the Construction System operation and bringing it all together ready for implementation on the case study project. To start the process of turning the theory of the Construction System into practice, members were selected from the project team by the author to lead the design and implementation of the working details of the Construction System into real and meaningful methods. These are known as cross-functional teams according Liker (2004), The Toyota Way principle 10. The team comprised:

- Offsite Manufacturing Manager;
- Planning and Production Control Manager;
- Construction and Logistics Manager;
- Case Study Project Managers, Engineers and Designers;
- Commissioning Manager;
- Procurement and Supply Chain Engineers;
- Supply Chain Members.

The initial activity was to agree upon a set of guiding principles, design parameters and ground rules so that decisions were made in the light of these and the team would not move forward unless each had been satisfied.

4.6.2.1 Guiding principles, parameters and ground rules

These were brought together from company policy, the case study project's particular requirements and the requirements for the development of the Construction System drawn from the research process. This provided a framework for the cross-functional teams to deliver the required outputs to meet the stated requirements. Whilst as Project Leader, the author had power to impose these actions upon the project team, all problems and potential solutions were discussed with all of those affected to collect their ideas and to get agreement on a path forward; then to make decisions by consensus, thoroughly considering all options and to implement decisions rapidly (Liker 2004). These are two of the ground rules set below – no.'s 3 and 4, and this was done in the development of the System. Three guiding principles were set by the team:

Principle 1 - Incident and Injury Free: *People returning home safely every day after a productive days work; minimise on-site labour; health, safety and quality shall be the over-riding objectives of the design (drawn from company policy);*

Principle 2 – Design to make the site one of assembly rather than construction: *Engage in systematic analysis of the elements and their interconnection; design for modular assembly; design for standardisation; design solutions for re-use; engage the internal and external supply chain to deploy expertise early in the design process – design around a product (drawn from company policy and the research process);*

Principle 3 – Use technology enablers: *Digital prototyping (3D drawing) is to be deployed throughout the project; fully integrated and co-ordinated; 3D common data structure; 3D intelligent objects provided by the internal & external supply chain (drawn from company policy and the research process).*

When considering the actual components that go together to form the complete M&E systems, parameters were set by the team against which selection was made. These are presented in table 4.5.

Table 4.5 Component selection parameters and purpose

Parameter	Purpose
Connectivity.	Interface specifications are to be set and met (Fredriksson, 2006), modules must be easy to connect together on site.
Maintainability.	Equipment must be able to be maintained easily when in use.
Commissionability.	Equipment must be commissionable when ready. Commissioning off-site is desired.
Use only reliable, thoroughly tested technology.	A proven process that works is to take precedence over new and untested technology (Liker, 2004).
Infection control.	Equipment must comply with hospital infection control standards.
Compliance.	Equipment must comply with prevailing specifications and standards.
Flexibility.	Equipment must be able to be modified or removed and replaced quickly and easily.
Modular and standardised.	The starting point is modular assembly; what cannot be modularised must be capable of being parts-kitted.
Manufacturable, buildable, consider setting-out and building tolerances.	Equipment must be available and capable of being manufactured to the best value. It must be capable of being transported and incorporated into the building through a small and simple series of tasks. Equipment must be capable of being incorporated from common setting-out points, and fit within specified building tolerances without modification.
Durable, sustainable, environmentally friendly.	Equipment is to achieve specified design life, and have minimal impact environmentally, and be capable of future disposal and/or re-use.
Best value.	Equipment is to be best value, not necessarily lowest cost.

As well as the parameters set out above; other ground rules are made to guide the team through the process, some of which were derived from Liker (2004), The Toyota Way principle 13:

"Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly." The ground rules:

1. In finding a solution, do not create problems for other aspects of design / buildability (derived from Liker 2004);
2. Do constructively criticise the solutions found (derived from Liker 2004);
3. Do discuss problems and potential solutions with all of those affected, to collect their ideas and get agreement on a path forward (derived from Liker 2004);
4. Do make decisions by consensus, thoroughly considering all options; implement decisions rapidly (derived from Liker 2004);
5. Do consider the timetable of the development when making decisions (derived from the team);
6. Do involve the supply chain (derived from the team);
7. Do not affect the town planning constraints (derived from the team);
8. Do not affect the medical planning constraints (derived from the team);
9. Do not impact on other issues such as fire, acoustics, hospital specification's etc. (derived from the team);
10. Do consider the impact of the solution on the hospitals operations (derived from the team);
11. Do find the technical solutions, do not allow programme and cost issues to inhibit innovation until the last responsible moment (derived from the team);
12. Record the process success and failure in a log (derived from the team);

13 How is each of the protocols to be measured in its success of delivery (derived from the team)?

These guiding principles, design parameters and ground rules set the scene for the team to start the process of designing the working details of the Construction System features into real and meaningful methods.

4.6.2.2 Planning and production control

This section describes how the cross-functional teams approached the overall planning of the project using reverse-pass scheduling, applying the Week-Beat method of scheduling and the Last Planner System of production control.

4.6.2.2.1 Reverse-pass scheduling

Whilst the project follows the steps in the value chain shown in figure 4.15, the Construction System planning methodology was to start the planning process with final critical activities first. A reverse-pass approach was taken meaning that the process started with the last activity first which was M&E systems commissioning and proving. This was to ensure that a robust well thought through commissioning programme was established that would prevent the commissioning management difficulties found by Dicks (2002). Traditionally commissioning of M&E systems is squeezed into the remaining time at the end of a project which is the result of delays and disruption to installation activities that can occur that cannot then be made up during the difficult commissioning period. The objective was to not allow this to happen and to ensure that the final critical activity in the process, the commissioning and proving operations, had delivered to it the M&E systems installed complete, commissionable and at the right time. So the commissioning sequencing and programming was agreed upon first. Figure 4.16 presents a typical traditional approach taken when planning construction projects. It starts with design which is pushed into procurement (buy what is designed), which is then pushed into manufacturing (make what is procured). Manufacturing, in terms of equipment and components then pushes into site installation (install what is made), which in turn pushes into, and invariably squeezes commissioning (commission what is built).

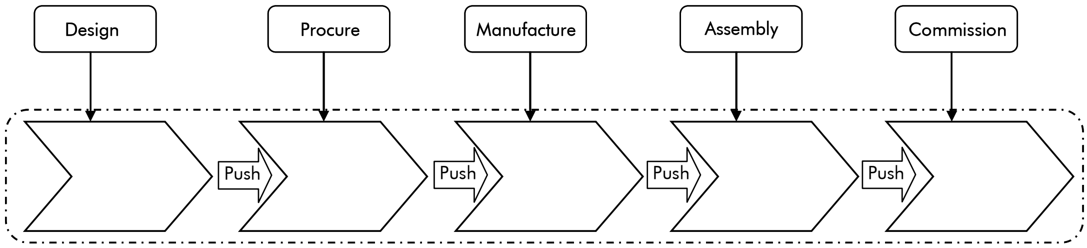

Figure 4.16 Traditional project value chain planning steps

This traditional value chain was reversed and is presented in figure 4.17. Commissioning was the first activity to be considered (have ready something commissionable). Once commissioning was established, installation activity (onsite assembly), manufacturing, procurement then design was considered (design, procure and manufacture something buildable – design for manufacture and assembly - DfMA). In effect, this is a pull system, with each customer in the project value chain getting exactly what it wants and when it is needed. This was done within the framework of the M&E design and the project strategic programme[23].

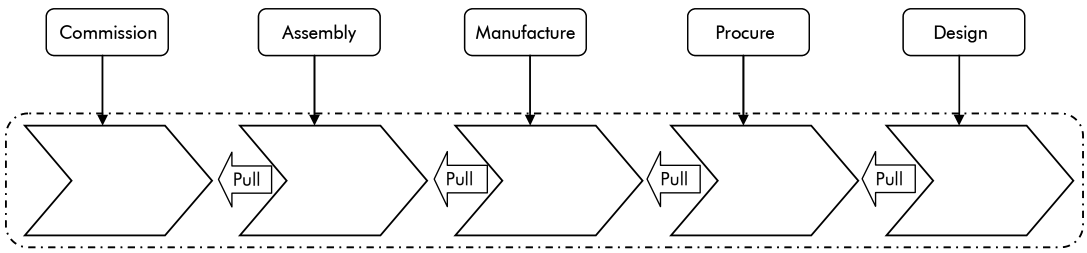

Figure 4.17 Planning steps with reverse-pass approach

23 Also known as the master schedule as an LPS term.

Time buffers were also generated and built into the start of the commissioning activities, the objective of which was to defend the commissioning period against any construction duration changes that may have occurred for whatever reason. The output of the reverse-pass scheduling was the generation of an integrated logic based master schedule setting out all of the design, procurement, component manufacture, onsite assembly and commissioning activities. The onsite assembly step was developed using the Week-Beat scheduling method.

4.6.2.2.2 Onsite assembly with Week-Beat scheduling

According to Rother and Harris (2001), the pace of production is one of the most critical considerations for the design of a process. Takt time is used to help synchronise the pace of production to the rate of sales. In the context of this research, the rate of sales must mean the rate at which the customer (the next step in the process) requires the previous work to have been completed so that theirs may start. Having right-sized the construction zone for a weeks work the rate of sales must be one week. So the pace of production to achieve this must also be one week. The Construction System was therefore designed to operate at this production pace and has been called the Week-Beat method, with teams carrying out their work in their own clear space, uninterrupted by other teams with their equipment and materials.

In Howell et al. (1993), it is described that productivity suffers when the output of one subcycle delays a following step or when resources required for one subcycle are engaged in another subcycle. The key issue is therefore balancing interdependent subcycles (Howell and Ballard 1999a) so that all steps of the operation are part of a continuous flow process. The Week-Beat method was designed to assure this key issue was addressed. The requirements for the Week-Beat are as follows:

- Each team has to work at the rate at which the previous team makes the working area available to them so as to provide a continuous flow of work (the rate of sales – takt time);
- The size of each team may be increased or decreased but the actual pace of physical effort is never changed (subject to resource management);
- Each team has to carry out their designated amount of work in the planned time so as to make the working area available for the subsequent trade team;
- Timing has to be such that each team can complete their work in the zone and move to the next zone without waiting for it to become available or starting early;
- The systems being installed have to be designed in such a way so as to facilitate this process;
- The rate at which each item of work is carried out is to pull materials onto the site, to the work area on a Just-In-Time basis, specifically for the task and without being stored on the site, in kit form, on mobile carriers or roll cages;
- Access equipment and tools are to be designed specifically for the area in which the work is to be carried out, and the rate at which the work is to progress;
- The rate at which each item of work is carried out is to pull drawings and information onto the site, being always the latest most up to date and approved for construction.

To achieve the production pace the building was divided into construction zones each being approximately 1,000 m^2[24] (zones 1-17, plantrooms 1-3) and is presented in figure 4.18.

[24] 1,000 m^2 for a construction zone is selected because this is a suitable size to enable a team to install the required amount of individual M&E work within a week period.

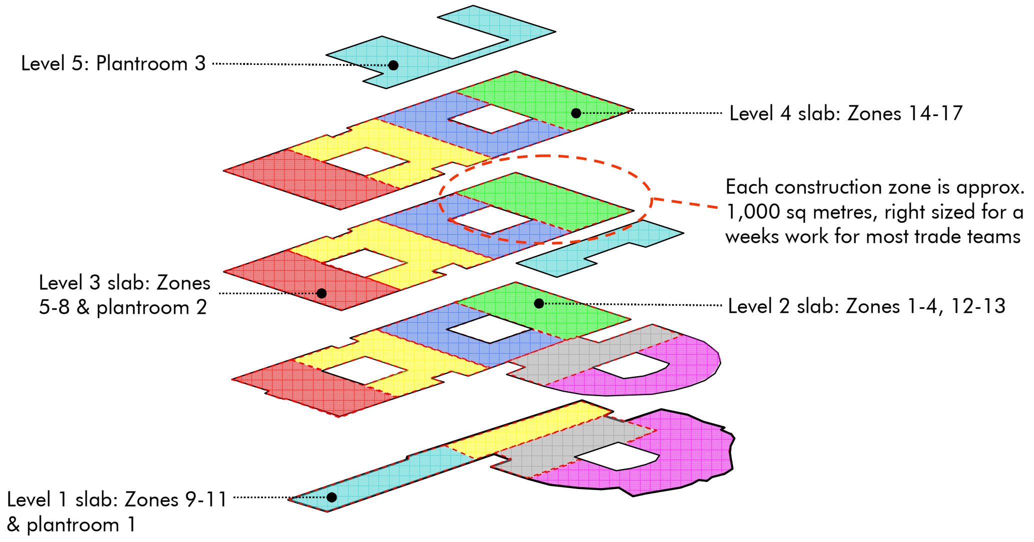

Figure 4.18 Maternity and Oncology construction zones

Within each construction zone M&E work had various sub-process activities, as did the building fabric works (dry-lining, ceilings, painting and flooring etc.). Table 4.6 shows the agreed sequences between each M&E process (MEP1, 2, 3 etc.) and associated building fabric processes (BFP1, 2, 3 etc.).

Table 4.6 Construction zone process and activity schedule

Process ID	Installation activity
BFP1	Mark out and fit dry lining header track.
MEP1	High-level first fix.
BFP2	Thin bed screed, dry-lining studwork and first side dry-lining.
MEP2	M&E drops within walls.
BFP3	Second side dry-lining, tape and joint, mist coat painting.
MEP3	Medical gas pipework, power and control cabling, wall mounted M&E equipment.
BFP4	Ceiling bulkheads, ceiling grid, service tiles for M&E devices, door frames.
MEP4	Ceiling mounted M&E equipment.
BFP5	Vinyl floor, final painting, doorsets and ironmongery, cupboards, fixed furniture.
MEP5	Final connections to equipment, WC's, baths, door mounted electrical accessories.
BFP6	Ceiling tiles (excluding commissioning access tiles), carpets and final clean.

Each of these construction processes are interrelated and therefore dependant upon each other to be complete as planned as a precondition. Figure 4.19 presents a template construction zone assembly process.

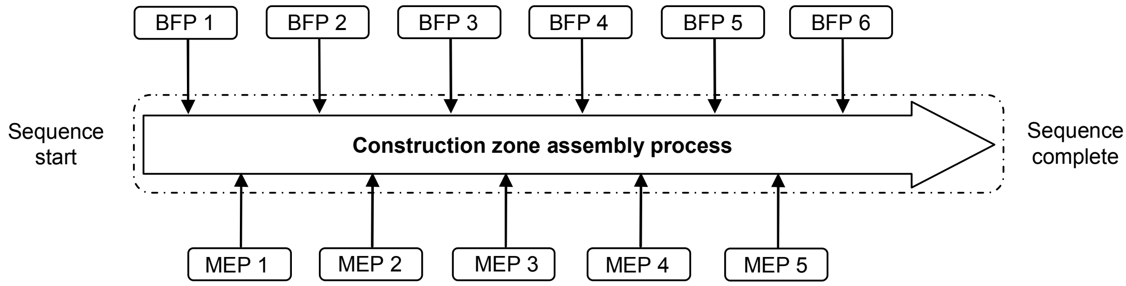

Figure 4.19 Construction zone assembly process (adapted from Court et al. 2009)

This shows the building fabric process (BFP1-6) and the M&E processes (MEP1-5). It starts with a designated construction zone made available for work and finishes when all works are complete and ready for testing and commissioning once adjacent areas and systems are ready. As seen in table 4.6 each BFP and MEP process activity has various sub-processes within it and MEP1 is presented in figure 4.20. MEP1 consists of at least five sub-processes each of these conducted by separate crews.

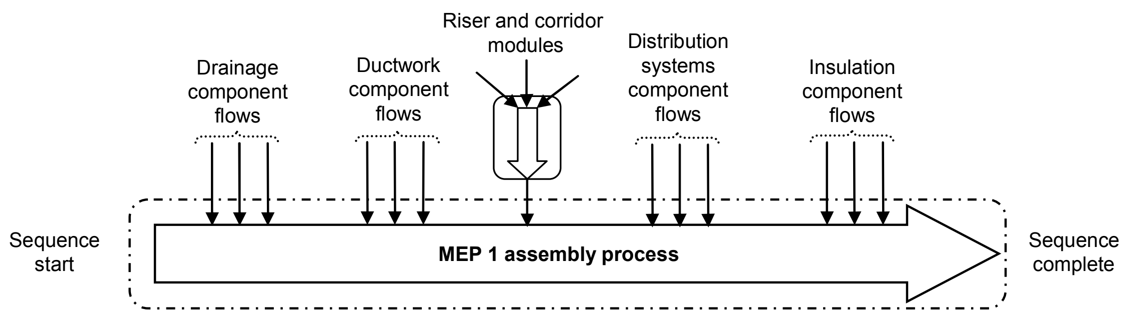

Figure 4.20 Mechanical and electrical process 1 (adapted from Court et al. 2009)

A template was developed which sequenced each sub-process commencing with BFP1, to completing BFP6 using the Week-Beat method. Here, each activity was allowed one week to complete its operation before moving on to the next zone, with no other operations being allowed unless separated by physical space in the construction zone. This is called parallel operations. The initial calculated cycle-time for this was 50 weeks however this revealed bottlenecks in the System. The solution to this was to close-schedule certain operations in the sequence and have other operations carried out in parallel to others. This is presented in figure 4.21.

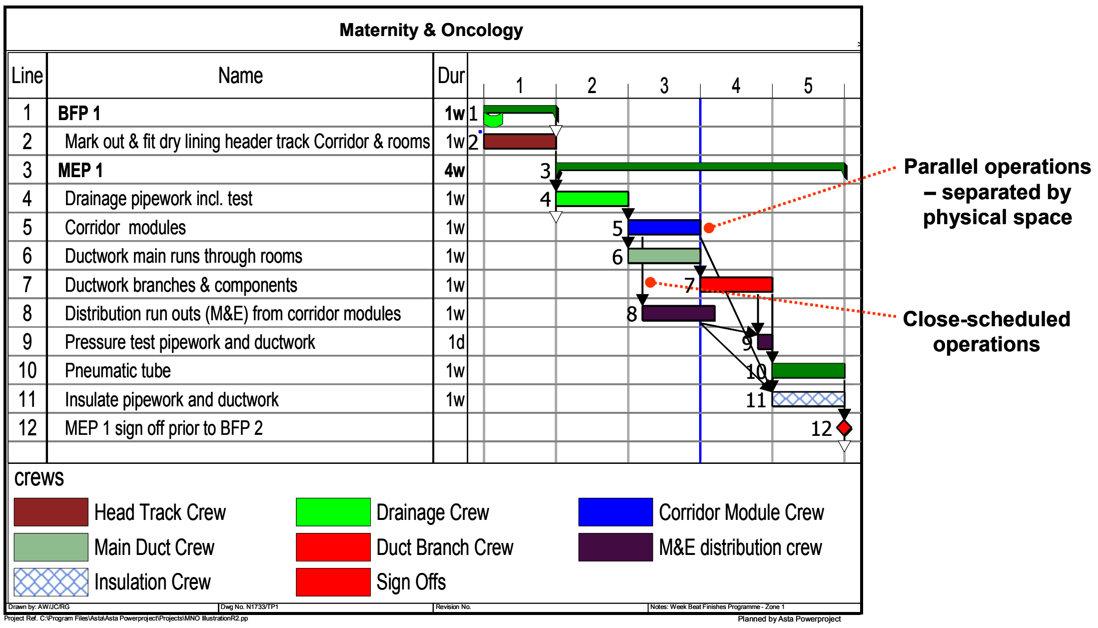

Figure 4.21 Close-scheduling MEP1 sub-process

Close-scheduling is a technique used in period batch control (Burbidge 1996) where following operations are started on a batch before the preceding operations have been completed on all the parts in the batch. As a result of this, in MEP1 the fitting of distribution systems from corridor modules, commences the day after the first four modules being installed. This in effect allowed accelerated work flow whilst not decreasing the time required for the work activity to be carried out.

The bottleneck[25] revealed in the construction sequencing was the requirement for four weeks for each key building fabric process for dry-ling operations within BFP2 and BFP3. The

25 A bottleneck in the system is work not fitting into the Week-Beat period.

method to overcome this was to elevate the bottleneck and to subordinate the following operations to its pace (Goldratt and Cox 2004). Here, four weeks for the bottlenecks in BFP2 and BFP3 were allowed and their following operations (MEP2 and MEP3) were subordinated to their pace. In order to maintain the Week-Beat a construction zone was further divided into equal quadrants, each approximately 250m² (or one quarter of rooms in the construction zone), allowing one week per zone quadrant for BFP2 and BFP3 operations, with following non-bottleneck processes subordinated to this pace. This is presented in figure 4.22.

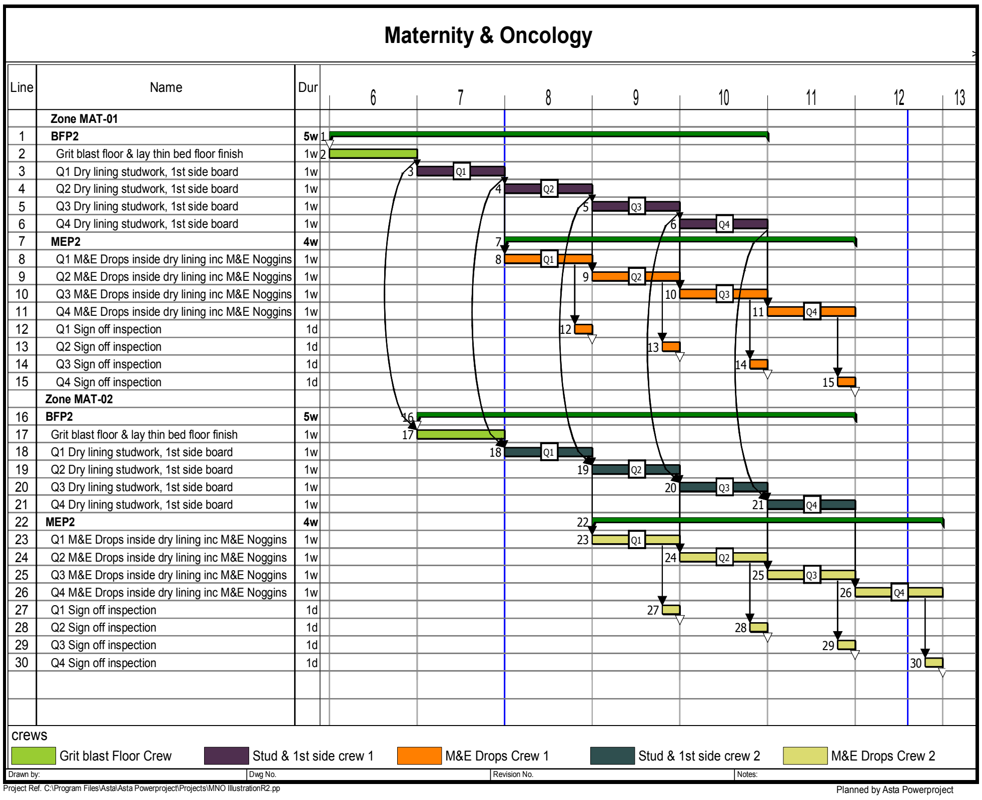

Figure 4.22 Elevating the bottleneck sub-process; dry lining and studwork

Construction zones were then close-scheduled a week apart meaning that a new BFP2 process team commences in a new construction zone one week after the first zone commenced and so on, this also maintains the Week-Beat. A construction zone cycle-time was finally agreed at 46[26] weeks and this is presented in figure 4.23.

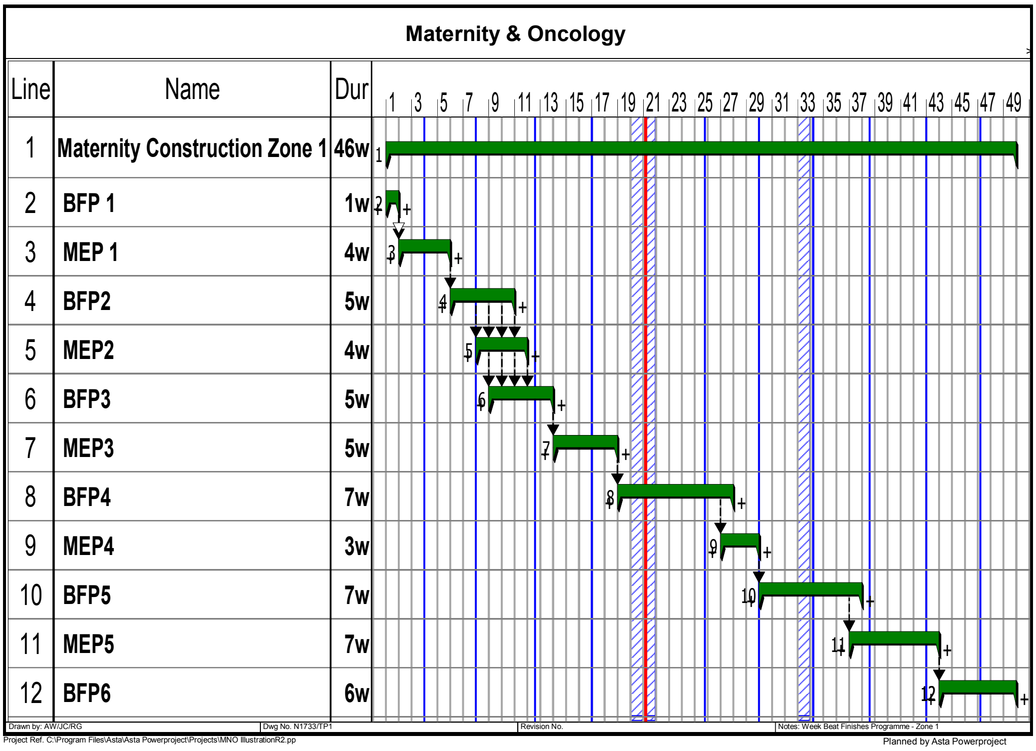

Figure 4.23 Maternity and Oncology 46 week construction zone cycle-time programme

Applying this to all 17 construction zones and plantrooms resulted in a 63 week total cycle time for all MEP operations and this is presented in figure 4.24. This generated a five week safety buffer in front of commissioning operations[27] and a one week safety buffer in front of the customer handover milestone. As has been stated, one of the requirements for the Week-Beat is that the size of each team may be increased or decreased but the actual pace of physical effort is never to change. This adjustment would be required to match resource

[26] Construction zones 9, 10 and 11 in the Oncology building had a 52 week cycle time due to different sequencing between BFP & MEP sub-processes as the result of increased floor to floor height.

[27] The commissioning programme was to be 12 weeks for both Maternity and Oncology as agreed by the cross-functional team.

levels to the actual workload in each construction zone as they will differ. This is to be done by resource management.

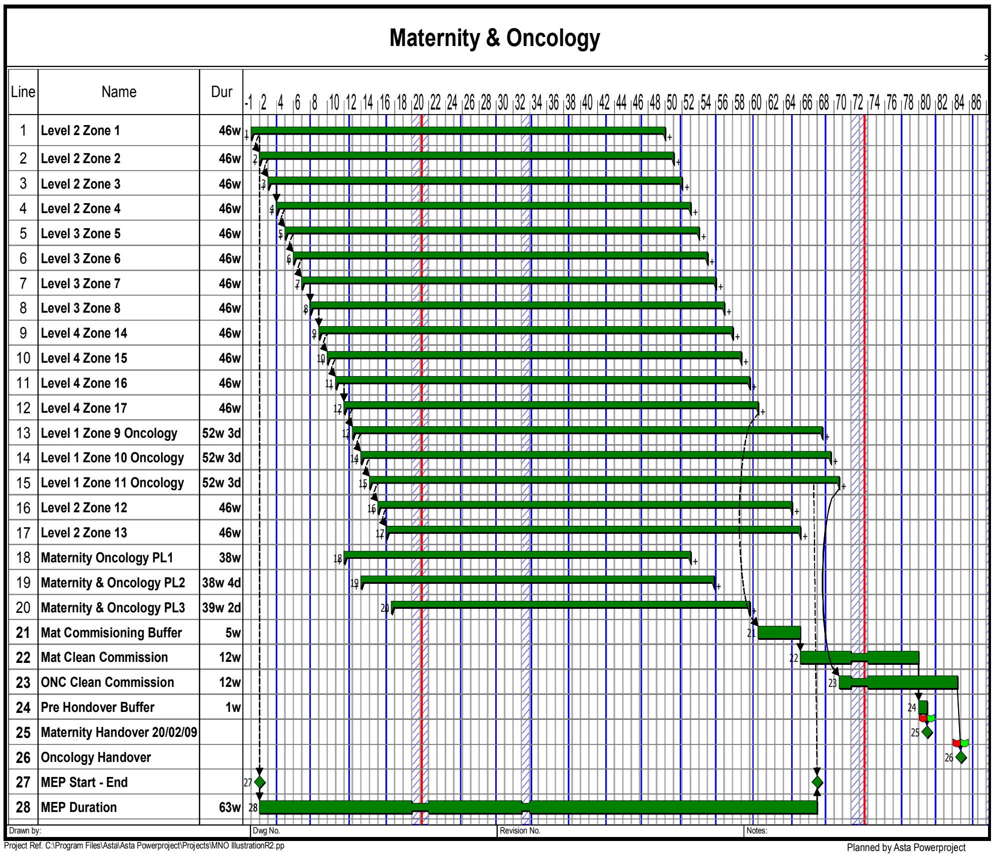

Figure 4.24 Maternity and Oncology total 63 week cycle-time programme

4.6.2.2.3 Resource management

The planned resource in the Week-Beat method needs to be managed to keep the operatives in productive work as far as possible. For each of the sub-processes in the planned MEP operations in the case study project, material take-off's were labour loaded to calculate optimum team labour levels required to complete the planned work within the Week-Beat allocation. The planned available time allowed per week was four days (Monday-Thursday), leaving Friday to pick up any working backlog items (incomplete items from previous work) and to make ready for the next weeks work. Labour could also be deployed elsewhere on the project on non-critical activities (M&E in staircases etc.). Leaving Friday clear allowed a time and resource buffer in the Week-Beat to compensate for variances in work load between different construction zones as each zone did not have the same amount of M&E systems. That said, to constantly match resources to the pulse, the M&E labour levels must be kept constantly monitored during the implementation phase to ensure that sufficient levels are deployed. Quantity differences also occur in the fitting of partition walls (BFP2 and BFP3 – dry-lining) due to the fact that some zones have more rooms than others. To overcome this, planned labour level was to allow only for the fitting of internal walls (those forming corridors and rooms), leaving the dry-lining of the inside of outer walls and staircases as working backlog. This was to be co-ordinated within the wider project team to ensure the timely fitting of any previous work (M&E drops in this dry-lining) prior to the dry-lining proceeding. This method would allow the partitioning contractor to maintain a constant labour loading but flexing it between planned works and working backlog items.

For most of CHt's activities, labour is directly employed and therefore would be costed by them. Where specialist sub-contractors are to be used, the Week-Beat method is to be priced into the value of the sub-contract works where their labour shall be managed by them but within the operational parameters of the Construction System.

4.6.2.2.4 Production control

Another Lean component of the Construction System which was to be deployed is the Last Planner System (LPS) of production control (Ballard 2000). LPS is a production planning and control tool used to improve work flow reliability and it adds a production control component to the traditional project management system (Henrich et al. 2005). LPS was to be deployed through each of the phases of the project with six week look ahead's and weekly work plan meetings. LPS has complimentary properties with the Week-Beat method because the six week look ahead's and the weekly work plan meetings screen and shield each week's planned operations in the Week-Beat operation. The use of LPS with the Week-Beat method anticipates stabilisation providing more predictable work-flow to enable the Construction System to function. It also will also use Construction Physics Seven Flows (Bertelsen et al. 2006) to screen the weekly activities and these flows are: information; materials; previous work; space; crews; equipment and external conditions. This method will drive the team to make ready all the areas of work and by using this constraints analysis only what can be done shall be placed in the weekly work plan. The look ahead shall always be done into the projects strategic programme and measurement of progress is to be checked back against this, which will enable corrective actions to be taken by the team as required.

4.6.2.3 Design

4.6.2.3.1 Basic and detailed design

Design is not the subject of this research project however the design process undertaken on the case study project was influenced by the Construction System. Design was to be produced by an M&E design specialist for CHt and the process was to follow BSRIA's technical note TN21/97[28] (Parsloe 1997), "Allocation of Design Responsibilities for Building Services Engineering". This is shown in table 4.7. In this process, the designer is responsible for sketch drawings, schematic drawings and detailed design drawings and CHt are responsible for co-ordination drawings, installation drawings, installation wiring diagrams and record drawings. The design process would include design for manufacture and assembly (DfMA) and designing around components pre-selected by the cross-functional teams as described in this chapter.

[28] Now superseded by BSRIA technical note BG 6/2009 – A Design Framework for Building Services 2nd Edition (Churcher 2009).

Table 4.7 Drawing definitions and responsibilities (from Parsloe 1997)

Drawing definition	Responsibility
Sketch drawing	Designer
Schematic drawing	Designer (2D)
Detailed design drawing - mechanical	Designer (2D)
Detailed design drawing - electrical	Designer (2D)
Co-ordination drawing	CHt (3D digital prototype)
Installation drawing	CHt / specialist sub-contractor
Installation wiring diagram	CHt / specialist sub-contractor
Shop drawing	CHt / specialist sub-contractor
Manufacturer's drawing	Manufacturer
Record drawing	CHt / specialist contractor

4.6.2.3.2 Digital prototyping

Digital prototyping (3D modelling) would allow CHt to use the design as a platform to produce its 3D model where all components in the model were objects from the project's digital library. The M&E systems were to be modelled by CHt's CAD (computer aided design) operatives inside a structural 3D model produced by the projects structural designer. This process enables digital visualisation and co-ordination, as well as the ability to schedule parts from the model. A project digital library was planned to be populated with objects that CHt already had together with those provided by suppliers and component manufacturers which would be pre-selected by the cross-functional teams. This would reduce the number of components in the digital library as only those pre-selected were to be used in the model and subsequently scheduled and procured. It was then made a pre-requisite that suppliers provide digital objects for their components in the purchase agreements to avoid the need for the CHt's modellers to develop these from scratch. Ductwork manufacturing drawings would also be produced from the model, allowing direct transmission of data to CHt's manufacturer's CAM (computer aided manufacturing) machinery. This was to avoid the waste of reproducing manufacturing drawings from traditional 2D layouts. Modular assemblies were planned to be objects within the model which in turn would have individual manufacturing drawings associated with them. The model would generate single service drawings, each being a layer from the parent model which would be coordinated and free of clashes (after a clash detection process). Actual drawings required would then be printed from the model into paper-space (a conventional 2D drawing) for use in the manufacturing and construction processes as required. A collaborative web-based document and information management system was then to be deployed on the project which would manage the flow of information from the project to the supply chain and those requiring information.

4.6.2.4 Procurement

Procurement was then to be undertaken in accordance with CHt's policies and procedures using national framework suppliers and sub-contractors already in CHt's supply chain. According to the author this isn't a Lean procurement practice because it involves non-relational contracting and competitive tendering, which is not a Lean Construction ideal. As Colledge (2005) reports, criticism of the (construction) industry as a whole in the past has focused on the inability of contracting stakeholders to engage co-operatively in the delivery of the client's objectives and an apparent inability to deliver on time cost and quality. It would appear, Colledge continues, that adversarial contracting approaches and the pursuit of individual company gain has resulted in a less efficient industry and lower levels of productivity and innovation (also reported in Latham 1994, and DETR 1998). The author could not influence this approach as it is driven by corporate policy from the centre of CHt and therefore was not part of the development of the Construction System. However, a Lean

Construction philosophy was written into the specialist sub-contract terms and conditions that sub-contractors would have to abide by. These particular contract clauses included:

- What is Lean Construction?
- Workflow Planning (Last Planner System of Production Control);
- Week-Beat Programming – Creating Workflow;
- Workplace Organisation; Tooling and Access Equipment;
- Team Working;
- Continuous Improvement Practices.

All of these were to be pre-requisites for sub-contract award along with other usual contract clauses particular to the case study project. The purpose of these Lean Construction pre-requisites was to ensure, as far as possible, that sub-contractors and suppliers engaged with the project's Lean method of working within the contractual framework allowed by CHt. These specialist sub-contractors, when engaged, would also form part of the cross-functional teams to collaborate where necessary in the Construction System development process.

For labour procurement at that time, CHt predominantly operated a self-delivery model meaning that most installation work would be undertaken by its own workers or labour-only sub-contractors with just specialist work undertaken by sub-contractors. By utilising the direct labour approach it was perceived that CHt would have greater control over the labour element of the project than it would with sub-contract labour, in other words "you can't control what you don't control". Specialists would include pneumatic tube conveyor system; thermal insulation; nurse call systems; fire alarm systems; refrigeration systems and medical gas systems.

4.6.2.5 Component manufacture

This particular phase of the research process resulted in the third paper submitted for the Engineering Doctorate and is described in Court et al. (2009). This paper (paper 3) is contained in appendix C, and is published in the American Society of Civil Engineers publication, the Practice Periodical on Structural Design and Construction (May 2009). This paper describes the design of the modular assembly and postponement components of the Construction System. The key elements reported in this paper are the logistics strategy; installation sequencing; approach to modular assembly and postponement for construction zones; construction zone and plantroom modules (type A parts); construction zone component flows (type B and C parts) and labour and associated cost forecast (expected benefits of the System). A further research paper describes the overall function of the site operations component (final assembly unit) of the Construction System (Court et al. 2007). This paper is not included in this thesis but is a part of the development of the overall System. The paper covers an important area of research within the IGLC community, which is the theory of Construction Physics. The paper was best in section when presented at the IGLC 15 conference in July 2007, Michigan, USA in the Championship: Production System Design.

Before the commencement of component selection, a site-wide logistics strategy had to be set. The component manufacture methodology had to fit within a logistics strategy to ensure synchronisation of component flows into site and the Week-Beat method of operation.

4.6.2.5.1 Logistics Strategy

The purpose of this logistics strategy was to communicate to the wider team and supply chain members the logistics intent. It was purposefully designed to reduce the waste traditionally seen in construction processes, i.e. inventory is a waste (and gets damaged lying around site);

workers waiting for parts is a waste; workers walking to get parts is a waste. These various forms of waste could be reduced with this strategy, which is:

- There will not be a big central store of parts waiting to be used or workers having to walk to and from stores to collect parts;
- There will be parts on site today, being what is needed tomorrow with inventory check-lists used to guarantee complete kits are provided;
- Modules (type A parts) will be delivered direct to the point of use by a logistics team and incorporated using mechanical lifting gear;
- A logistics team will deliver kits of type B parts for the next days work on carriers which are moved straight to the point of use and replenishing type C parts into mobile work centres according to use.

Having set the logistics strategy, the next step was the classification of all of the components that go together to form complete M&E systems, and this would be done by utilising ABC parts classification.

4.6.2.5.2 ABC parts classification

The logistics strategy was to set the thinking for how components were to flow into the site. Due to the fact that components were to be procured according to their type then their supply chain source needed to be understood. A Lean ideal for the IGLC Championship: “Prefabrication and Assembly” is to simplify site installation to final assembly and commissioning (Ballard and Matthews 2004). In this ideal, products used in the building process have been divided into made-to-stock (MTS) and made-to-order (MTO). Therefore, components for the System were further categorised into MTS and MTO types. This categorisation is presented in table 4.8 for MEP1-5 and plantroom assembly processes.

Table 4.8 ABC parts classification by MTS and MTO

Process	Type A - MTO	Type B - MTO	Type B - MTS	Type C - MTS
MEP1	Corridor modules.	Ductwork, fittings and accessories; composite brackets; fire stopping cassettes.	Pipework and fittings; electrical tray and fittings; insulation.	Nuts, bolts, washers, screws, clips etc.
MEP2	None.	Pre-formed conduits; modular wiring and accessories.	Pipework and fittings; electrical tray and fittings; insulation.	Nuts, bolts, washers, screws, clips etc.
MEP3	Electrical panels; integrated plumbing systems (IPS); bed head modular units; medigas valve boxes (AVSU's).	None.	Armoured cable; data cable; low voltage control cable (fire alarm, nurse call, BMS etc.); modular wiring for lighting and small power.	Nuts, bolts, washers, screws, clips etc.
MEP4	IPS front panels; bed head modular units front panels; AVSU front panels; ultra clean theatre hoods; medical pendants.	Radiant heating panels; light fittings; ventilation grilles and diffusers.	Ceiling mounted electrical accessories.	Nuts, bolts, washers, screws, clips etc.
MEP5	None.	WC's; Bath tubs.	Wall and door mounted electrical accessories.	Nuts, bolts, washers, screws, clips etc.
Plantrooms	Air handling units; chillers; plantroom modules; generators; electrical panels (HV, LV etc); water tanks.	Ductwork, fittings and accessories; composite brackets.	Pipework and fittings; electrical tray and fittings; armoured cable; data cable; low voltage control cable (fire alarm, nurse call, BMS etc.); insulation.	Nuts, bolts, washers, screws, clips etc.

This table shows all components that form the complete M&E systems for the hospital and it includes all capital equipment such as air handling units, high and low voltage electrical panels, generators etc. These components are expensive type A parts and are made by CHt or its supply chain. The only type A parts made by CHt in its manufacturing centre will be corridor modules[29] (MEP1 type A parts) and plantroom modules (plantroom type A parts). Traditionally the components within these modules are fitted on site by operatives engaged in site cutting, drilling and assembly work and elevation of parts into final position, as has been previously described in the literature search findings for the current state of the research problem (step 2).

All components are to be pre-selected by the team and where required are also to be supplied in 3D object format for inclusion in the project's 3D model. This allows the number of supplier's components used in the System to be reduced and a project object library to be compiled from which components are selected and procured.

The strategy is essentially a Just-In-Time (JIT) system and according to Forza (1996), a production system which culminates with JIT is very efficient if everything runs perfectly but is extremely fragile if there is any kind of problem whatsoever. Further, and in order to be able to function in a Lean system, all the resources being used in the production process have to be foreseeable and reliable. The Construction System had this potential to be fragile as it was not, at that time, embedded into CHt's operations or tried and tested (because it is a case study undergoing trial implementation) therefore, component flows into the project had to be foreseeable and reliable in order for the Construction System to work as planned. In Hopp and Spearman (2001), safety stock and safety lead times can be used as protection against these problems. Safety stock should be used to protect against uncertainties in production and demand quantities, while safety lead time should be used to protect against uncertainties in production and demand timing. These countermeasures were built-into the Construction

[29] Riser modules were not able to be supplied for the case study project due to certain design issues that are not reported in this research project. These did feature, however, in later phases of the project as the design issues were overcome by the team.

System and resource capacity buffers were built into the site operations component. This was done by planning each week activity into four days of the week which sizes the team to carry out the work required for the designated activity. This provided a one day capacity each week to buffer against any unplanned event that may have occurred. If the work was completed in the planned duration the team would then be able to clear backlog items or make ready to move to the next construction zone in the sequence. Figure 4.25 presents the component flows into the site by MTO and MTS suppliers, showing safety lead time and safety stock buffers and their location in the supply chain.

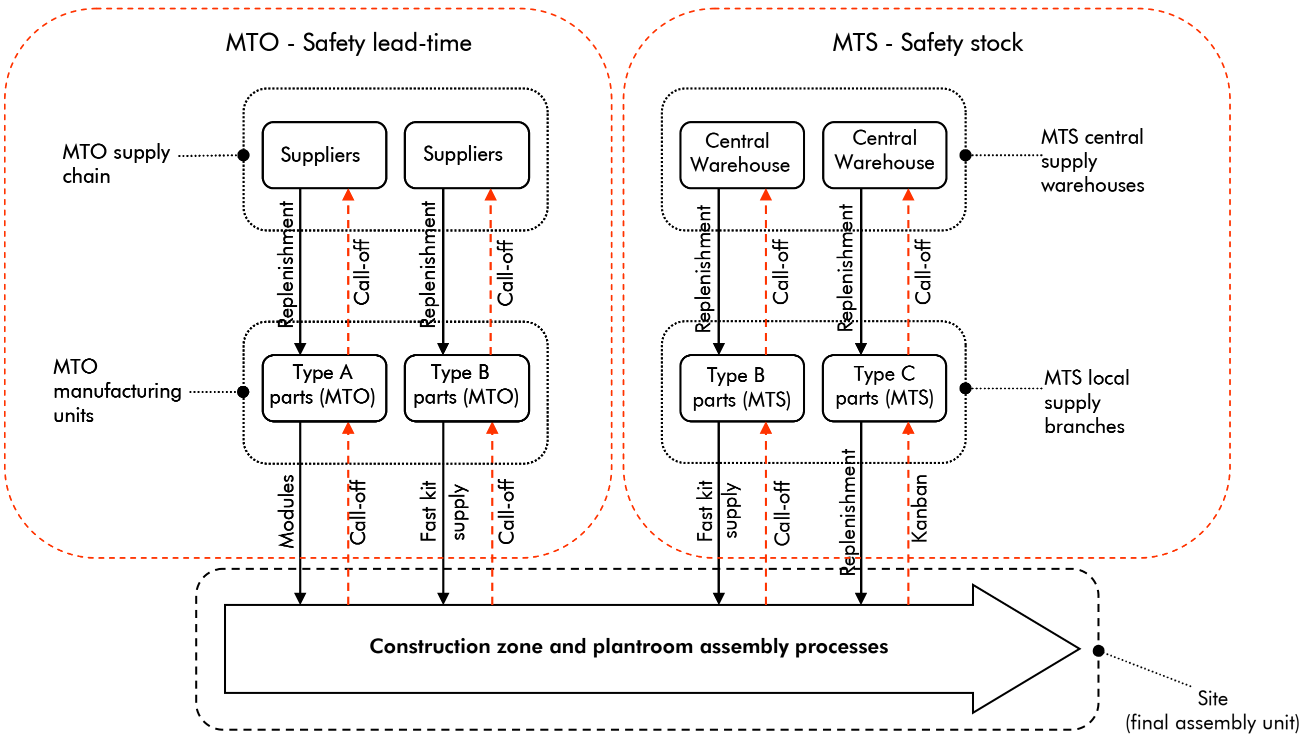

Figure 4.25 MTO and MTS component flows into site

Safety lead time in the System had to be provided in the supply chain for MTO type A and B parts. MTO type A modules, given their size and complexity, would be required to be delivered directly to the point of use (not postponed), and their lead time was to be incorporated into the master schedule. A safety buffer of at least two weeks would then built-in, dependant upon the module type, to protect against any disruption to production and site demand. MTO type B components have a lower lead time than modules and again safety lead time for these was also to be built into the master schedule.

Safety stock in the System was planned to be provided both on site and in the supply chain for MTS type B and C parts. These parts were to be purchased from national framework suppliers and held in stock at a local branch. The kits to be provided to site were to be delivered 'today' for use 'tomorrow' giving a one day stock buffer on site. As described previously, individual works within a construction zone is to take one week to complete in the Week-Beat cycle and supplier's agreements would be to keep two zones of parts in stock at the local branch. Replenishment was to be signalled when parts for a zone are depleted, giving a one week safety stock buffer in the System, but offsite. Site replenishment from the local branch would signal replenishment from the central warehouse to the local branch which would replenish it with parts for a zone every week. The central warehouse would operate a 12 week stock-turn giving an 11 week safety stock buffer further back in the System; this was to rely upon global project quantities being advised by the project to the supply chain which had to be done. All components were planned to be delivered to site by the supply chain to then be handled from the point of delivery to the point of use by a site logistics team operated by CHt.

4.6.2.5.3 Modular assembly - construction zone and plantroom modules (type A parts)

The corridor modules were to be assembled in CHt's manufacturing centre (with its own labour), to then be transported to site in batches of four on assembly, transportation and installation frames (ATIF's). These are then to be lifted with mechanical hoists and bolted to cast-in unistrut inserts running in tram-lines along corridor positions in the concrete soffit. The ATIF is then returned to the manufacturing centre for re-use. Each construction zone has approximately 16 modules and four were planned to be fitted each day, completing each zone within the Week-Beat period. Fundamentally each module is a standard platform (the ATIF and bracketry), with the components within it (pipes, cable containment etc.) being configured specifically to the requirements of the space it serves. Such a strategy provides mass customisation (Skipworth & Harrison 2004). Plantrooms are at this stage divided into manageable chunks, such as capital plant items, plantroom modules and distribution modules, all of which are MTO. Plant components such as pump sets, pressurisation units, valve stations etc. are to be grouped together and assembled offsite into plantroom modules by CHt; these are also to be wired and insulated at the manufacturing centre to further reduce the amount of work onsite. Interconnections between plant modules and risers are planned to be site assembled also using pre-assemblies and kits of associated parts. All other type A parts are to be MTO and assembled in suppliers own manufacturing centres using their own direct labour.

Pull signals (call-offs) for these components were to be directed to manufacturing in accordance with the strategic project programme, with safety lead time built-in to manufacturing periods to protect against uncertainties in production and demand timing that could occur.

4.6.2.5.4 Postponement and parts kitting - construction zone and plantroom component flows (type B and C parts)

The approach to manage the flow of components to the point of use was to kit the specific parts for the MEP operation and postpone its delivery until it would be needed. The kitting itself was to be carried out using MTO and MTS suppliers (at their premises) as re-packing centres and de-coupling points. Bertelsen et al. (2006) describe previous experiments using this approach. The decision was made that each of the components selected shall be quick-fit, commercially available and tried and tested technology. Small bore pipework for water and drainage was to be either push-fit, crimp-fit or clamp type. Larger bore pipes would be welded and flanged, but made offsite by CHt.

Electrical trays would be basket, trunking or ladder type which fit together quickly with snap-on couplings. Power cables for small power and lighting was to be a modular plug-and-play connectable system configured on site from standard but MTO components. Larger armoured cables for main power supplies would be standard type MTO and be delivered on cable drums. Extra low voltage (ELV) cables (data, BMS, nurse call etc.) which are also standard items were to be on small drums or boxed as appropriate. Each of these components were to be delivered to site in purpose made mobile roll cages or similar. All type B MTO components were to be made in suppliers own manufacturing centres using their own employed labour.

Pull signals (call-offs) for type B MTO components were to be directed to manufacturing in accordance with the strategic project programme with safety lead time built-in to manufacturing periods to protect against uncertainties in production and demand timing that could occur. Type B and C MTS components would be held in supplier’s premises until signalled for replenishment by the site teams.

As previously described, two days of stock were planned to be held on site in the particular construction zone (replenished every two days) with stock of two construction zones held in suppliers local branches (replenished every week) and stock for twelve construction zones held in their central warehouses. This would ensure that safety stock was provided in the System for these components. This parts kitting was planned to be carried out by the suppliers Just-In-Time to suit call-offs from the site teams.

4.6.2.6 Onsite assembly

4.6.2.6.1 Inbound and outbound logistics

As has been described previously all components once delivered to site would be handled directly to the point of use by a logistics team. This team, to be headed by a team leader, would then manage inbound and outbound logistics for all M&E work activities. Inbound logistics was to include offloading deliveries, co-ordinated with other non M&E deliveries for distribution to the point of use. Outbound logistics was to include the removal of all empty stillages and ATIF frames and re-loading these on back-hauls to the relevant supplier / manufacturer for replenishment. Outbound logistics would also include managing physical waste out of the workplace and for segregation into central skips for onward disposal.

4.6.2.6.2 Workplace organisation

During the course of the design of the Construction System further data was collected for the design of trade team specific mobile work cells. This was conducted in collaborative planning sessions with representatives from electrical workers, mechanical pipe workers and duct workers. The parameters set were to ensure that each trade team would have a complete set of equipment including appropriate personnel protective equipment (PPE); tools; lighting; access equipment; workbenches; parts trolleys; walkie-talkies and everything that will be needed for each individual trade team. This process produced designs and led to the manufacture of workplace equipment for each of the sub-process trade teams and included (but was not limited to):

- Information and drawing boards (example in figure 4.26);
- Mobile workbenches (example in figure 4.27);
- Mobile parts storage units and stillages (examples in figure 4.28, 4.29);

- Access equipment;
- Appropriate tools, lighting and walkie-talkies.

Figure 4.26 Mobile drawing and information board

Figure 4.27 Mobile workbench

Figure 4.28 Mobile parts storage unit (type C – MTS)

Figure 4.29 Mobile parts stillage (type B – MTS)

4.6.2.6.3 Training and induction

Prior to the work commencing on site, all operatives would be required to undergo induction and training. This would include an IIF module, a site specific induction module (operatives would be required to pass a test before being allowed to work on site) and a Methods of Work module. This last module introduces the operatives to the Construction System and how shall operate. It also includes a module called "Ergonomics in Construction". This outlines the HSE statistics on workers suffering from MSD's as a result of working in construction and how by designing tasks, work spaces, controls, displays, tools, lighting, equipment and thus the ergonomic workplaces designed as a result, that this would fit the worker's physical capabilities and limitations. The obligation to be placed on the attendees during this induction is that each of them shall be required to comply with the company's vision and values, its IIF policy and the operation of the Construction System for the benefit of themselves and CHt together.

Following the site induction each trade team would be provided with a specific information pack containing: the induction register; training certificates; method statement; safety toolbox talks; daily activity briefings; daily labour allocation sheets; logistics plan; "Introduction to Ergonomics in Construction" pack; specification of materials; parts suppliers catalogues and instructions; COSHH[30] information; programme; drawings and test and inspection sheets. The method statement would be the main vehicle for describing to the worker how the work will be carried out and would include: a scope of works; sequence of works; specific programme; competency of those involved; equipment to be used; emergency procedures; emergency contact telephone numbers; responsible supervisors; monitoring of the work method; PPE requirements; environmental data, monitoring, review and briefing process; risk assessments and task sheets. Each worker was to be briefed on their particular method statement during the induction and training by CHt and would be required to confirm their intended compliance to the method statement by signing it when briefed. Daily activity briefings would also be given to each team by the team leader and feedback collected to help in developing the IIF culture on the project.

4.6.2.7 Commissioning

As described earlier in this thesis, the commissioning process is the final step in the project's value chain prior to the facility being handed over to the customer. Reverse-pass planning

[30] Control of Substances Hazardous to Health.

sought to ensure that a robust well thought through commissioning programme was established first that would prevent the commissioning management difficulties found by Dicks (2002). Also, according to the CIBSE commissioning management guide (2003), the commissioning of buildings and building services is vitally important to the safe and energy efficient operation of buildings but it is not always carried out – or carried out systematically. The CIBSE commissioning codes set out clearly and systematically the steps required to commission building services in a proper and timely manner and will make a significant contribution to achieving properly commissioned buildings.

The commissioning programme and the steps within it were produced by the case study project Commissioning Manager together with the team and incorporated the commissioning codes recommended by CIBSE. An expected benefit of the Construction System was to provide all of the installed M&E systems on time and to the correct requirements for the next step in the process – commissioning – so that the building was commissioned properly, in a timely manner, systematically and to the satisfaction of the customer.

4.6.2.8 Construction System operation – bringing it all together

Figure 4.30 presents how the Construction System operates in practice. It shows MEP1 to MEP5 each being fed by the Construction Physics Seven Flows. Each MEP process was to be managed by individual team leaders and a process supervisor, with overall management by the production managers. Also shown is the inbound and outbound logistics team that were to feed the MEP processes with type A, B and C components and the removal of physical waste from the workplace. Allocation of last planners is also indicated with each of these attending the weekly work plan meetings to be held.

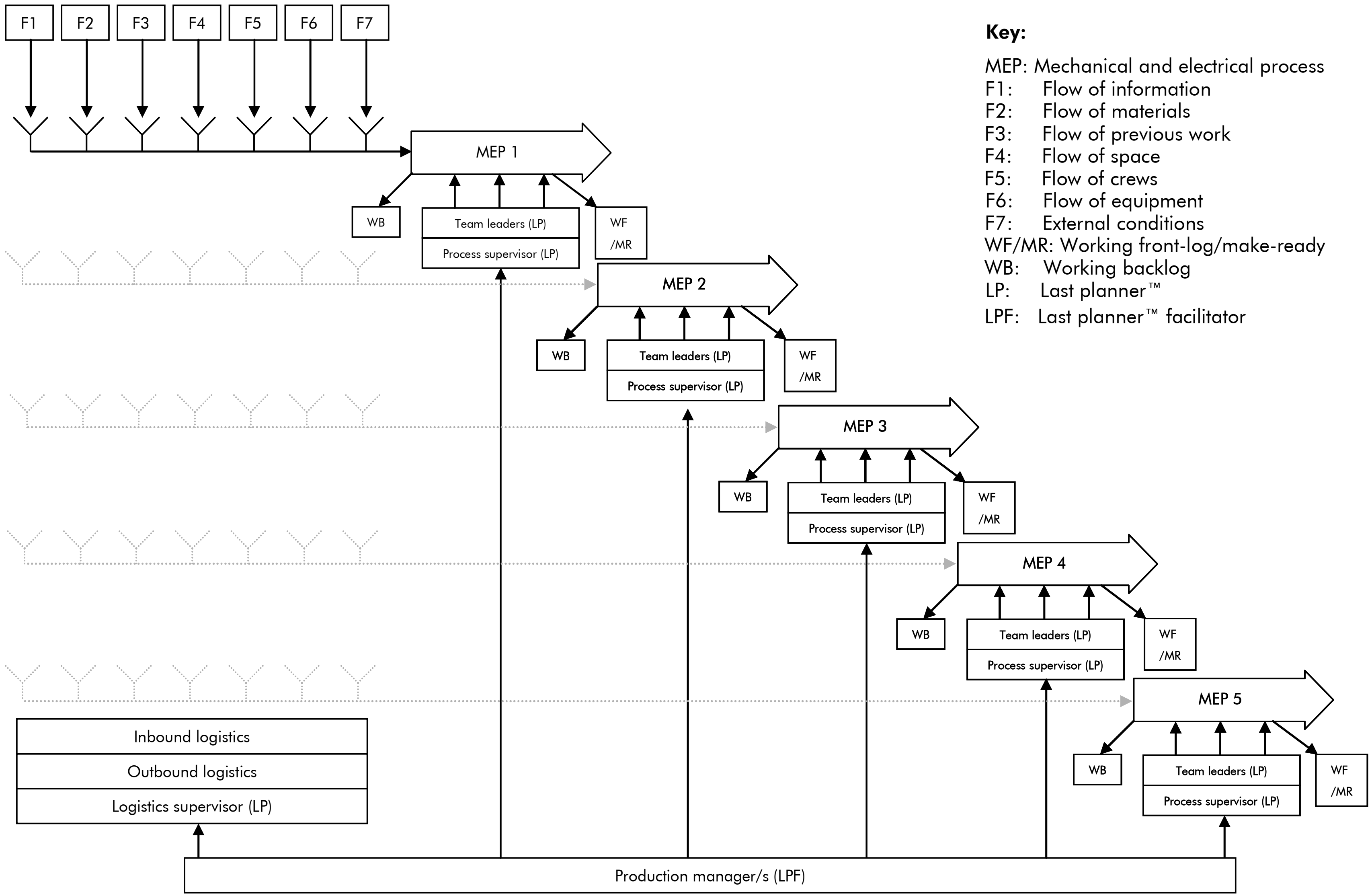

Figure 4.30 Construction System operation – bringing it all together

4.6.2.9 Summary of step 5

This section has described the selection of the case study project and the process of turning the theory of the Construction System into practice with real meaningful methods that can work when implemented. The next step in the research process is the setting of realistic objectives and measurement of success for implementation.

4.7 STEP 6: SETTING OF REALISTIC OBJECTIVES AND MEASUREMENT OF SUCCESS FOR IMPLEMENTATION

The aim for the performance of the Construction System is set out in chapter 2 of this thesis which is to improve site operations, making them safer for the worker and to improve productivity as a countermeasure to the problems in UK construction that face CHt. This therefore must be measureable in terms of health, safety and productivity outcomes to gauge if the implementation of the Construction System has been successful. This step in the research process continued the action research method and used a large scale experimental study expanding upon the pilot study reported in Court et al. (2005). In this study, a project was chosen as the experiment, and a hypothesis, which is a statement about cause and effect that can be tested, was set as follows:

"Lean as an antidote to labour cost escalation on complex mechanical and electrical projects".

Labour was the independent variable to be manipulated in that experiment, and the outturn cost of labour was the dependent variable, which was observed as the outcome of the experiment. In order to manipulate the independent variable (labour), Lean interventions were designed and applied to the project. These were: standardisation of components;

standardised work sequencing; mobile work cell and ergonomic access equipment. In this larger, case study experiment, labour would still be the independent variable to be manipulated by the application of the Construction System. The dependent variable would be the health, safety and productivity outcomes of the experiment that could be measured. The laboratory in which to conduct the experiment was to be the Maternity and Oncology case study project during a sample period, this being the planned onsite assembly time for the M&E works across all construction zones and plantrooms.

4.7.1 Measurement of productivity outcomes

For productivity and labour cost and utilisation, targets were set to decrease the amount of labour required to carry out the work and to facilitate improved effectiveness and productive work for those that are required onsite. When combining offsite modular assembly and postponement with the Lean site operations component of the Construction System and then projecting the labour required performing all planned operations, a target of 35% less onsite labour was set. This target was derived from a comparison of calculated estimates of labour times between conducting the work using traditional methods and by using the Construction System as described in this thesis. For all MEP processes, including plantrooms, the traditional method is estimated at 202,800 hours, with the construction method estimated at 131,840[31] hours. This equates to a difference of 70,960[32] hours between the two methods which is the 35% reduction in onsite hours. Also, because of the simplification of the assembly process, a lower ratio of skilled to semi-skilled operatives will be required, which

[31] Previously reported as 131,040 hours in Court et al. (2009) and now corrected to 131,840 hours (authors typing error).

[32] Previously reported as 71,960 hours in Court et al. (2009) and now corrected to 70,960 hours (authors typing error).

reduces the average hourly cost of labour, potentially further reducing the outturn labour cost of the project. A reduction in total cycle-time was also predicted using the System however, at this stage of research this was kept as a time buffer between M&E construction and commissioning. This reduction in forecasted labour does not represent an overall labour saving as work has shifted offsite for modular assembly, it does however represent a reduction in labour onsite.

4.7.2 Measurement of Health and Safety outcomes

It is an important point to note that health outcomes could not be measured within the scope of this research project. These are illnesses caused by the work itself as reported in Gibb 2006. These are known as slow accidents causing workers to be injured over time as a result of their work as opposed to occupational safety accidents which can be measured as they occur. For safety outcomes, an important objective of the System was to have zero reportable accidents and this was monitored using the CHt's accident reporting system.

Success itself is not just about achieving these targets, i.e. by having less operatives' onsite, or even a reduced cycle time carrying out the work. These can be considered only as a means to an end. Success must mean delivering a safer, profitable project which the customer is satisfied with, on time, on or below budget and to the right quality. Success for CHt means sending all workers home safely after a productive days work, good productivity achieved leading to no labour cost escalation as reported in Court et al. (2005), and delivering a profit for CHt. It also means setting a benchmark for productivity in the company, as CHt do not have a productivity measurement system at the time of writing this thesis.

4.7.3 Summary of step 6

This section has described the realistic objectives set for the measurement of success for the implementation of the Construction System. The next step in the research process was actually implementing the Construction System on the case study project and testing the solutions designed.

4.8 STEP 7: ACTUAL IMPLEMENTATION AND TESTING SOLUTIONS

4.8.1 Commencement of the case study project

This step continued the action research method and involved starting the implementation of the Construction System on the case study project. The project process commenced through each of the steps in the value chain presented in figure 4.15 using the design, procurement and component manufacture processes described earlier in this chapter.

Onsite assembly work commenced in August 2007, with planned completion of the installation activities due in October 2008, a 63 week total cycle time for all construction zones, including plantrooms (the sample period). The trade teams were deployed in the agreed sequences as described earlier and in accordance with the Week-Beat method. Figures 4.31 to 4.40 show actual images of mobile works cells; ATIF corridor modules; inbound parts kits and outbound backhauls of stillages; mobile parts trolleys; ergonomic scaffolds; ergonomic plasterboard handling equipment and plantroom modules.

Figure 4.31 Mobile work cell for drainage crews in their own clear space

Figure 4.32 ATIF module ready for installation, type A materials (MTO)

Figure 4.33 Kit of parts for ventilation systems on mobile carrier, type B materials (MTO); inbound logistics

Figure 4.34 Outbound logistics (backhaul), returning mobile carriers for replenishment

Figure 4.35 Mobile carrier for pipework components, type B materials (MTS)

Figure 4.36 Ergonomic access equipment, walk-up mobile scaffold

Figure 4.37 Mobile carrier for modular wiring components, type B materials (MTO)

Figure 4.38 Ergonomic materials handling equipment for dry-lining boards

Figure 4.39 Plantroom module, type A materials (MTO)

Figure 4.40 Plantroom module, type A materials (MTO)

Throughout the implementation of the Construction System during the sample period, weekly work-plan meetings were conducted using the Last Planner System, and actual labour used was monitored with daily labour allocation sheets. This tracked all operatives time used in the Construction System working either directly for CHt or for its specialist sub-contractors. The data collected was then utilised to compare an estimated traditional approach to a target Lean and agile approach (using the Construction System method) and then to the actual recorded cumulative hours used on site during the sample period.

4.8.2 Summary of step 7

Step 7 of the research process began the implementation of the Construction System on the case study project through each of the construction zones and plantrooms. The next step was monitoring the System in use and gathering data in order to assess findings and results emerging during the implementation.

4.9 STEP 8: FIRST RUN STUDY WITH RESULTS EMERGING

4.9.1 Progress in the sample period

All M&E construction zone processes (MEP1-5) and plantrooms were complete at the end of October 2008 (week 66), with the exception of the completion of major customer variations to the Oncology department and working backlog items[33]. These customer variations resulted in approximately 60% of this department (2 construction zones) having to be remodelled. During the sample period 80% of electrical testing was complete; 80% of water systems pressure testing was complete; 50% of ELV system testing was complete (building management systems, fire alarms etc.); 90% of voice and data system testing was complete and clean commissioning commenced (air and water system balancing). High voltage power-on was achieved June 2008, and water-on to the building was achieved August 2008. Hand-over to the customer occurred in March 2009 for the Maternity department and June 2009 for the Oncology department, both on time and to budget. During this sample period, certain findings emerged relating to productivity and labour cost, and Health and Safety, which are now reported.

[33] Working backlog is defined here as any minor incomplete works and rework items (such as snagging, missed items of work etc.).

4.9.2 Findings emerging from the sample period

The findings emerging from the sample period have fallen into two sets and are reported in Court et al. 2008 (paper 4 contained in appendix D), and Court et al. 2009a (paper 5 contained in appendix E).

4.9.2.1 Productivity and labour cost findings

Productivity and labour cost findings emerging from implementation have fallen into two sets. The first set was the results and analysis of the benefits from the use of corridor modules in lieu of a traditional installation method. This sub-process within MEP1, the installation of corridor modules made offsite, is reported in Court et al. (2008) and is contained in appendix D. This paper (paper 4) was presented at the IGLC 16 conference in Manchester, UK, in the Championship: Prefabrication, Assembly and Open Building. This paper reports on the findings from this case study using the IMMPREST[34] toolkit. Pasquire et al. (2005) describe the IMMPREST toolkit as a tool for assessing the benefits derived from the use of modular offsite assembly (hereafter known as S&P[35]) against what would have been traditional installation methods had this been used. The benefits were classified into six categories: cost; time; quality; health and safety; sustainability and site benefits. The traditional option described in the assessment is: "site installation of corridor mechanical and electrical services using traditional methods" (known hereafter as traditional) and the S&P option described is: "modularising corridor services using the ATIF method". The paper reports that 1,568 actual onsite hours were used elevating and connecting together a total of 196 ATIF modules in comparison to 22,320 hours estimated using traditional methods, which would have required

34 Interactive Model for Measuring Preassembly and Standardisation in construction.

35 S&P meaning standardisation and preassembly as an IMMPREST term.

various trade teams completing the required work all working at height. This is a 93% reduction, with an 8.62% cost benefit also reported. This cost analysis compared an estimate of traditional method against actual ATIF method including: basic materials; material waste; labour (including supervision and testing); productivity losses; transport costs; site equipment; rectification and rework costs and design costs. This is presented in table 4.9.

Table 4.9 Comparison of estimated traditional costs to actual S&P costs (values are £000's) from Court et al. (2008)

IMMPREST Items (by exception)	Traditional (estimated)	S&P (actual)
Basic materials	£197.09	£260.42
Material waste	£15.86	£3.96
Labour including supervision and testing	£273.67	£205.81
Productivity losses (25% of labour only)	£53.12	£0
Transport costs	Included	£44.84
Plant and access equipment	£40.80	£4.08
Rectification and rework	£10.62	£1.28
Design (assembly drawings)	£0	£19.80
Total	£591.16	£540.19
Variance: Traditional to S&P	**£50.97 (8.62%)**	

Basic material cost for S&P is higher than traditional due to offsite manufacturing centre overheads. This cost also includes an amortised cost allowance for the use of the ATIF frames, considered as an asset to the total project. Actual basic material cost for both methods was considered equal. Material waste for the traditional method was estimated higher than S&P due to increased probability of wastage onsite. Traditional labour cost was estimated using the M&E installation "Times Guide" (Luckins 2003, 2004) using a bill of materials (BOM) from the S&P manufacturing drawings.

The Luckins "Times Guides" assume average times under average conditions and installing good quality materials with good quality trained workers. No other site difficulty factors were included. S&P labour cost is the actual cost incurred and includes manufacturing centre overheads and the onsite cost to install ATIF modules and connect them together. Productivity losses means a cost factor estimate of the productivity losses possible between the different methods, including weather, stoppages, damage, theft and interferences etc. The estimated cost of this was assessed as 25% of traditional installation labour only to demonstrate this variable. As can be seen, the value of this variable provides the benefit assessed between the different methods. In other words, if estimated productivity losses for the traditional method were zero percent there would be no cost benefit of S&P. This is unlikely in the opinion of the authors and according to previous research (Hawkins 1997). This measured average overall productivity as 37% on the UK projects monitored. Any actual cost for S&P loss of productivity is included in the actual offsite S&P labour cost. Transport costs for the traditional method is included in the estimated basic material costs. A much higher actual cost was necessary for S&P as this was required to deliver the ATIF modules from the manufacturing centre to site and then a back-haul cost to return the ATIF's to the manufacturing centre for re-use. More plant and equipment was estimated for the traditional method and would have been required for each trade cycling through the site carrying out their work. Rectification and rework is estimated to be higher for a traditional method than S&P due to the increased likelihood of errors by many trades site fitting thousands of parts at high level (see table 1 in paper 4 contained in appendix D) when compared to simply elevating and connecting ATIF modules with a small team. Assembly drawings were required for the S&P method for manufacturing purposes; these would not have been required for a traditional method. The cost benefit reported here helps to overcome the barriers to offsite assembly found by Goodier and Gibb (2005) who report that, from their survey, the belief is that using offsite (manufacture) is more expensive than traditional construction and is the main barrier to the increased use of offsite in the UK.

The second set of results combines the first set of results with those emerging from the implementation of the Construction System through all mechanical and electrical processes and is reported, together with the health and safety findings, in Court et al. (2009a). Certain results from this paper are presented in figure 4.41[36]. This presents a comparison of hours for a traditional approach (curve A); the Construction System approach (target Lean and agile – curve B); actual hours booked (curve C) and actual hours booked minus unavoidable delays (curve D).

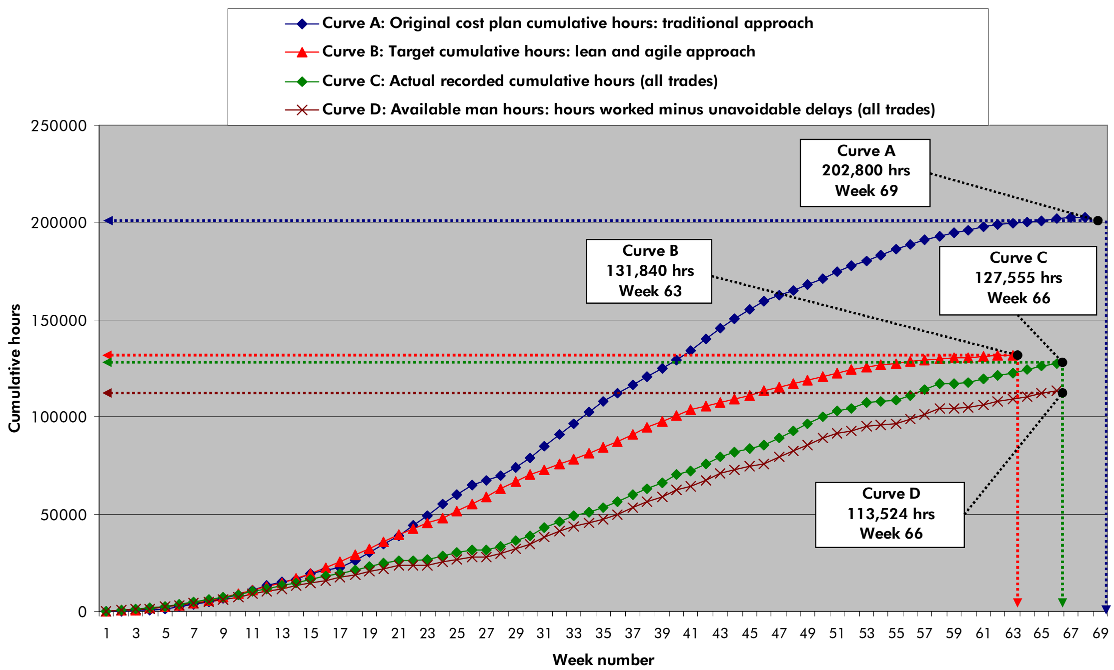

Figure 4.41 Comparison of traditional approach, target Lean and agile approach, and actual hours booked, with actual hours minus unavoidable delays shown

Curve A is the predicted cumulative labour hours and cycle time for a traditional installation method (for all work including sub-contractors originated from the project cost plan). This

36 This analysis includes the onsite labour installing ATIF corridor modules described previously.

shows **202,800 hours with a 69 week cycle time.** This curve is the benchmark against which the Construction System method is measured (planned – curve B, and actual – curves C and D). 202,800 hours is derived from 2,535 pair man weeks which is calculated as follows:

2,535 (pair man weeks) x 2 (men per pair) x 40 (hours per week) = 202,800 hours.

Curve B is the target predicted cumulative labour hours and cycle time after applying this Construction System method. This shows **131,840[37] hours with a 63 week cycle time.** This is the expected outcome. 131,840 hours is derived from 1,648 pair man weeks which is calculated as follows:

1,648 (pair man weeks) x 2 (men per pair) x 40 (hours per week) = 131,840 hours.

Curve C is the actual cumulative labour hours and cycle time recorded during the sample period. This shows **127,555[38] hours with a 66 week cycle time**. This is the actual outcome.

Curve D is the actual cumulative labour hours minus unavoidable breaks. This shows **113,524 hours (unavoidable breaks equate to 11% of actual time) with a 66 week cycle time.**

The onsite assembly finished at week 66 when all work was complete, this is shown as the final point of curve C, in figure 4.41. Following an analysis of the data, the measured benefits are presented in table 4.10.

One of the expected benefits of using the Construction System was a 35% reduction in onsite hours and a six week cycle time reduction. The actual benefit achieved using the

[37] These are paid working hours and therefore already adjusted for unavoidable delays. Workers are paid for a 45 hour week (excluding overtime if worked) and for their lunch break.

[38] These are also paid working hours and therefore already adjusted for unavoidable delays.

Construction System was a 37%[39] reduction in onsite hours and a three week cycle time reduction. The actual onsite hours improved from target by 3% (before unavoidable delays) but the expected cycle time benefit of six weeks reduced to an actual of three weeks. As described earlier, this was due to the client changes to the Oncology department which was not able to be accommodated in the target cycle time period. However, the labour hours for this were absorbed within the actual hours recorded.

Table 4.10 Table of measured benefits

Curve comparison	Description	Data	Benefit
A to B	The expected benefit (target)	202,800 hours minus 131,840 hours	**70,960 hours (35%)**
		69 weeks minus 63 weeks	**6 weeks**
A to C	The actual benefit	202,800 hours minus 127,555 hours	**75,245 hours (37%)**
		69 weeks minus 66 weeks	**3 weeks**
B to C	Improvement to target	131,840 hours minus 127,555 hours	**4,285 hours (3%)**
		63 weeks minus 66 weeks	**-3 weeks**
B to D	Improvement to target after unavoidable breaks	131,840 hours minus 113,524 hours	**18,316 hours (14%)**
		63 weeks minus 66 weeks	**-3 weeks**

As described earlier, Hawkins (1997) reports that the UK projects monitored had an average overall productivity of only 37% when compared to observed best practice. Using the method presented by Hawkins, a similar overall productivity calculation was made. To achieve this, available hours, as defined by Hawkins, were calculated (curve D). This represents recorded

39 The 37% saving in onsite hours does not represent a saving in labour cost, as these hours contribute to the labour budget for offsite manufactured components.

actual man hours minus unavoidable delays such as lunch and tea breaks[40]. This represents working hours available.

Overall productivity for the sample period was then calculated using the definition of overall productivity in Hawkins (1997):

$$\text{Overall Productivity} = \frac{\text{Output}}{\text{Available Time}}$$

Where:

- OUTPUT is a measured quantity of installed material to a defined requirement. The physical output is converted to units of time by employing an earned hour's concept based upon best practice installation times.
- AVAILABE TIME is the total working day minus unavoidable delays such as lunch and tea breaks.

Using this definition and hours from figure 4.42:

$$\text{Overall Productivity} = \frac{131{,}840 \text{ hours}}{113{,}524 \text{ hours}} = 116\%$$

Where:

- 131,840 hours is the total earned hours from the target Lean and agile approach (using best practice installation times – the Construction System).
- 113,524 hours is the booked hours at completion (the sample period) minus unavoidable delays (lunch and tea breaks), tracked using the System.

[40] On average, this is one hour per day per worker: 30 minutes for lunch break; 15 minutes for morning break; and 15 minutes for afternoon break.

Therefore, an overall productivity of 116% was achieved using the System, which compares favourably to the BSRIA findings of an average overall productivity of only 37% when compared to observed best practice for the projects in that case study research. This comparison needs to be viewed with a degree of caution, as the calculations shown reflects all of the M&E installations on the case study project compared with BSRIA's findings which represent an average overall productivity for only ductwork, hot and chilled water pipework, and cable management systems. This is treated by the author as a suitable benchmark from which to measure the performance of the Construction System against. Previous figure 4.41 includes time for all labour on site, which is the company's own direct labour and that of its sub-contractors. Of concern to the company was the impact that direct labour cost escalation can have on the projects outturn profitability (Court et al. 2005). Therefore an analysis of the company's direct labour hours was also undertaken. This is presented in table 4.11.

Table 4.11 Budget versus actual direct labour hours during the sample period

Budget direct labour hours	**Hours**
Budget hours	121,646
Variation hours agreed	11,429
Total budget hours	**133,075**
Actual direct labour hours	
Actual hours booked for the sample period (including supervision and non-productive overtime)	107,973
Further hours to complete (variations and working backlog)	15,680
Estimated final hours at completion	**123,653**
Forecast saving in hours	9,422
Forecast % hours saving	**7%**

This table presents a comparison between budgeted direct labour hours (excluding sub-contractor hours) and actual direct labour hours for the sample period, these being the workers actually employed by the company. It can be seen that a saving of 7% was achieved using the Construction System. After the sample period, a total of 15,680 hours was reserved to complete customer variations and working backlog elements as described previously.

4.9.2.2 Health and Safety findings

In terms of safety outcomes from the sample period, the case study project had zero reportable accidents (defined as injuries resulting in more than three days off work for the injured party). 19 minor injuries occurred during the sample period however and these were recorded in CHt's accident reporting system as they occurred. Each accident reported was categorised into: accident type; date of accident; primary cause; summary details of accident; underlying causations; behaviours; injured body parts and injury type. These have been included in appendix G of this thesis. An overview of the place of accident, behaviours and primary causes are as follows.

Place of accident: 8 were not at the place work itself; 11 occurred at the place of work.

Behaviours: 2 were non-compliance with procedures; 9 were human error; 7 were personal factors (carelessness, negligence etc.); 1 was a communication failure.

Primary cause: 3 were exposure to a harmful substance; 4 were slips / trips; 1 was contact with plant and machinery; 3 were moving / falling object, 4 were "other"; 4 were handling / lifting or carrying.

Whilst this is not an acceptable outcome given the interventions made with the Construction System, manual work itself is still at the core of the System and this factor will keep exposing the worker to the risk of minor injury. Of particular note, when studying these accidents, was the workers behaviour; all but one of the accidents could have been avoided if the worker complied with procedures and paid more attention to avoid carelessness. This could be overcome with more routine training given on the behavioural aspects of accident causation.

Human error could also be reduced with more attention given to further error-proofing the installation work itself in the future.

From a health perspective, what benefits did the worker derive from good ergonomics and workplace organisation for their wellbeing? According to Gibb (2006) the often delayed onset of (health) conditions following exposure (to occupational health risks) should drive us to look for solutions and do something about the problems. The interventions made in the project, by the Construction System methods, were about providing solutions to the health risks that would otherwise have been faced by the workers had these not been made. They were about protecting workers from work related ailments such as MSD's through better management and reduction of their exposure to the causative factors (Gibb 2006). Occupational health is about risk management and in this project the risks were managed by applying the workplace organisation and other methods implemented in the Construction System. This was achieved by undertaking the following:

- Providing cast-in inserts (to fix modules to the concrete slab) to avoid the need to drill overhead into concrete for large fixings;
- Providing walk-up scaffolds or scissor lifts to avoid the need to climb ladders inside traditional scaffold systems;
- Providing handling equipment and workbenches to avoid the need to bend over and work or kneel on the floor, which in turn decreases the physical workload of the worker (Sillanpaa at al. 1997);
- Providing modular assemblies with mechanical aids to lift them, which avoids the need to cut and manually elevate components overhead, working at height. This also enables employees to maintain an improved posture when connecting and testing the modules (HSE 2000);

- Providing mobile trolleys for tools, components and materials etc. which avoids the need to carry and move things around with manual handling;
- Having all materials stored in mobile trolleys at the workplace, exactly where they are needed, thus avoiding the need to walk around looking for and carrying things to where you need them;
- Enabling simpler assembly tasks with pre-assemblies and quick-fit components and thereby avoiding workers being engaged in too much site cutting, drilling and assembly work and elevation of parts into final position (Hawkins 1997).

The Construction System is an attempt to reduce the occupational health risks that construction (M&E) workers face and to fit the work to the worker as far as reasonably practicable. Due to the time lag between the cause and effect in occupational ill health, it was not possible to measure the benefit of these interventions in quantifiable terms within the scope of this research project. Also, without significant medical research and ethical compliance, there was no way of knowing a workers health condition prior to working on the case study project. As such, the need would have been to measure in excess of 100 M&E worker’s physical condition, prior to and after their involvement in the Construction System on the case study project during the sample period, and then draw conclusions from the findings. Whilst this was not within the scope of this research project, testing the ergonomic interventions made is an area worthy of further research. The ergonomic equipment provided on the case study project will, it is predicted, contribute to a significant reduction in the muscular load on the workers, as found by Sillanpaa et al. (1999). What can be said therefore, is that the Construction System does contribute to reducing the causative problems that lead to work related ailments, and because of this has the workers wellbeing and sending them home safely at the end of a productive days work at its core.

Having assessed these direct measureable results from implementing the Construction System, further observations of the System in practice we were made. These relate to breakdowns and how they were managed (lessons learned), and the impact of the quality of work offered to those workers engaged within the system (de-skilling or re-skilling).

4.9.3 Lessons learned

The Construction System is by no means perfectly formed and complete, it has undergone continuous improvement since the commencement of its implementation. The main features of the System have however worked which are the LPS production control method; ABC parts classification; modular assembly; postponement with parts kitting and the site operations. The use of LPS provided stabilisation which allowed work to flow, however, disruptions and breakdowns occurred whilst operating the System during the sample period. These disruptions were as a result of one of the Construction Physics Seven Flows (Bertelsen et al. 2006) failing for various activities i.e. lack of information, materials, previous work, space, crews, equipment or external conditions. Nevertheless, because of the rigour, discussion, route cause analysis and collaboration as integral parts of the LPS weekly work plan meetings the project team were able to manage the breakdowns and re-plan the work accordingly. During the weekly work plan meetings, each planned activity was screened using the seven flows and failures were analysed and collaborative corrective action taken accordingly (within the strategic project programme). In term of continuous improvement, these weekly work plan meetings can be considered as the projects continuous learning cycles which can be related to Deming's PDCA[41] cycle (Deming 1986). The reasons for failures in the System were identified and needed to be improved (the **Plan** to improve). The team then

[41] Plan; Do; Check; Act.

did the change required to improve the problem (the **Do)**, followed by checking to see if the improvement had worked (the **Check)** and finally acting on the improvement (the **Act)** by implementing the change as a routine part of the Construction System. Certain important lessons learned from implementing the Construction System on the case study project are contained in appendix H of this thesis. Finally, opportunities exist during future implementation of the System, in the combining of location based scheduling with the capability of 4D[42] CAD, which would help to visually display the Week-Beat strategy and would build upon the research conducted by Jongeling and Olofsson (2007).

4.9.4 De-skilling or re-skilling?

An attempt was made to provide a quality of work for the worker as has been previously described in this thesis. This is discussed by Granath (1998) describing Volvo seeking to provide its workers this quality of work as well as efficiency of production. He suggests that a system that offers professional meaningful work is better than those that only offer unskilled or semi-skilled work. The aspects that signify professional work are control over methods, time and quality plus the responsibility to plan ahead and the knowledge needed to reflect on work done. Quality of work also means good ergonomics, appropriate working tools and a good working environment. So has the Construction System, with its modular assembly approach, with parts kitting using push-fit / plug and play components provided this, or because of the simpler work undertaken due to the Construction System, has this de-skilled what they otherwise would have done on a traditional project? If this is the case then a quality of work has not been achieved. Whilst the impact, or otherwise of this, is not the subject of this research project, it is worthy of comment.

[42] 4D adds the planning dimension to 3D drawing.

The Construction System is claimed by the author to be a process innovation that incorporates existing technological innovations to M&E products and this is what Wilson (2000) refers to as alternative systems, components, materials and innovative methods. This technological change that has already occurred in the UK M&E construction, as a result of these product innovations, will have an effect on the skills of M&E workers and needs to be examined with further research.

The Construction System utilises quick-fit pipework systems, modular wiring systems and modular assembly (offsite manufacturing). As described in this thesis, each of the components used was selected to be quick-fit, commercially available and tried and tested technology. For example, small bore pipework for water and drainage is either push-fit, crimp-fit or clamp type. This technology has been in use in the UK since the 1990's within the primary sectors in which CHt operates. 95% of pipe systems under 100mm diameter in use today are from this technology, between 200mm and 400mm diameter this drops to approximately 70% and then over 400mm this drops again to approximately 10%. The overall average of pipework systems using this technology in the UK is 70%. Throughout its projects 85% of pipework systems installed by CHt are below 400mm diameter and for the higher size ranges welded systems are used which are made offsite in their manufacturing centre. All of this is done already in CHt irrespective of the Construction System. Also in use in the UK since the 1990's is modular wiring systems for small power and lighting, and nearly all large healthcare projects, under construction today, use this technology as does this case study project. As has been described, CHt is a major provider of offsite manufactured M&E modules and strives to use this capability today on all of its projects. Examples of other M&E systems that do not have this degree of technological change are ductwork, large cable and ELV cable installations.

The Construction System cannot be accused of only offering unskilled or semi-skilled work as this is as a result of the technological change that has already occurred in the M&E industry as a result of product innovation. All that is taken away from workers, as a result of the Construction System, is the unsafe and wasteful effort seen on traditional projects that has been described in this thesis. What the System is doing however, is providing safer, more effective and productive work for the benefit of the worker and CHt together.

Added to this is Howell and Ballard's (1999) claim that workers have more autonomy in production decisions and enriched jobs as a consequence of the Lean principles regarding distributed decision making, multi-skilling and pursuit of perfection. Also, Wilson (2000) found that when using innovative M&E installation techniques and products, in addition to the improvements in productivity, many other benefits for the whole construction team were produced. These benefits include:

- Improved working practices and buildability;
- A more efficient well trained and motivated workforce via staff training in innovative working methods;
- Recognition as an innovative company.

The author believes that the System is in fact re-skilling M&E workers in modern methods of construction and will lead to a new breed of well trained, multi-skilled construction assembly workers with good working conditions who are relatively highly paid. Finally, both Green (1999) and Jorgensen and Emmitt (2008) miss the safety argument in their criticism of Lean Construction previously described in thesis. Surely by providing safer more effective and productive work that benefits the worker and CHt together, is better than not doing Lean Construction at all and ignoring the problems faced today that places workers at risk of injury and creates poor productivity? The author believes it is.

4.9.5 Summary of step 8

This section has described the results emerging from the implementation of the Construction System on the case study project the Maternity and Oncology building. The results emerging are showing that because of the implementation of the Construction System, the case study project has had the following benefits:

- A 37% reduction in the number of operatives required onsite thereby exposing less workers to lower risks of injury leading to zero reportable accidents;
- Improved workers wellbeing by providing good ergonomics, a good working environment and simpler assembly tasks for those required on site;
- Reduced process waste thereby improving productivity leading to a 7% saving against the direct labour budget allocation;
- Achieved 116% overall productivity when compared to that found by BSRIA;
- Successfully developed an innovative frameless ATIF M&E module where a 93% reduction in on site labour was achieved together with a 8.62% cost benefit;
- Completed onsite assembly on time thereby not compressing commissioning periods leading to handing over the built facilities on time and to budget to the customer's satisfaction.

4.10 CHAPTER SUMMARY

This chapter has described the actual research undertaken through each of the research steps using the chosen methods on the case study project. The aim of the research was to improve site operations for CHt, making them safer for the worker and at the same time improving productivity, thereby avoiding labour cost escalation and the subsequent margin slippage that can occur as a result. This was achieved by achieving the six stated objectives through the eight steps of the research process (the ninth step being the production of this thesis). The research identified the issues that cause poor productivity and health and safety performance in M&E construction and developed a conceptual system using Lean methods from other industries to overcome these issues. It then developed the conceptual Construction System into real and meaningful methods that were applied and tested on the case study project during the sample period. The results emerging from the implementation of the System have been described and lessons learned have been recognised and implemented back into the System. The next chapter concludes the research undertaken.

CHAPTER 5 FINDINGS AND IMPLICATIONS

5.1 INTRODUCTION

This chapter concludes the research and discusses its contribution to existing theory and practice, its impact on the industrial sponsor and on the wider industry. Finally, the chapter provides recommendations for further research and a critical evaluation of the research undertaken.

5.2 CONCLUSIONS

5.2.1 Achievement of the stated aim and objectives

The overarching aim of this research project was to develop and implement a new way of working for CHt in order to improve the performance of its projects site operations, making them safer for the worker and to improve productivity as a countermeasure to the problems that CHt faces in the M&E industry within the UK construction sector.

In order to achieve this aim, six specific objectives were defined:

Objective 1: To reveal and understand the issues that lead to poor health, safety and productivity performance;

Objective 2: To reveal and understand Lean methods in use in other industries;

Objective 3: To develop a conceptual Construction System that adopts Lean methods from other industries that can be applied to M&E construction;

Objective 4: To turn the theory of the developed System into practice with real and practical methods that is able to be applied to a case study project in the real world;

Objective 5: To set realistic and achievable targets against which the System can be measured during implementation;

Objective 6: To implement the System on a live case study project and to measure the results emerging during the implementation.

These objectives have been met and satisfied through the achievement of each of the research process steps described in the previous chapter. This research process has concluded with certain findings emerging from the implementation of the Construction System which leads to meeting the overarching aim of the research project.

The key findings of the research project are described in the last chapter of this thesis in terms of the results emerging from the implementation of the Construction System and because of this implementation the case study project has had many benefits. The project needed 37% fewer workers onsite than would otherwise have been required if a traditional method had been used. This has meant that the reduced numbers of operatives were exposed to lower risks of injury because those required onsite were provided with good ergonomics, a good working environment and simpler assembly tasks. As a result of this, zero reportable accidents occurred on the project; however, it is acknowledged that minor injuries still happened. These can be reduced in the future with more training given to workers on the behavioural aspects of accident causation and with attention given to error-proofing the assembly work itself. In addition, manual work was at the core of the onsite assembly process which was a factor in the causative problems experienced. This also needs attention in the future to help reduce or even eliminate these factors.

From a workers health perspective, the interventions made in the project, by using the Construction System methods, were about providing solutions to the health risks that would otherwise have been faced by the workers had these not been made. These were about protecting workers from work related ailments such as MSD’s through better management and reduction of their exposure to the causative factors. The Construction System methods have contributed to reducing the causative problems and because of this has the workers wellbeing, and sending them home safely at the end of a productive days work, at its core.

In terms of productivity, the Construction System has reduced process waste traditionally seen in construction as revealed in this research project. Through utilising the System thus reducing this waste, the case study project has achieved 116% overall productivity which compares favourably with that found by BSRIA in their research project who reported only 37% for the four UK projects monitored (Hawkins 1997). Also, a 7% direct labour cost saving was made meaning that the project gained control of this large project cost variable that, if not controlled in such a way, can lead to margin slippage on projects (Court et al. 2005). Of great importance also is the customer, and for the case study project the customer had the built facilities delivered on-time, on budget and commissioned properly to their satisfaction.

The findings show that the Construction System is a successful set of countermeasures that acts as an antidote to the problems that CHt faces in the UK M&E construction industry. The transformation that has occurred is the creation of a step-change in undertaking M&E construction work, which has realised a significant improvement in performance for CHt that has “Transformed Traditional Mechanical and Electrical Construction into a Modern Process of Assembly”.

5.2.2 Is it a Lean System?

The System is built on Lean principles, the goal of which is to eliminate any human activity which absorbs resources but creates no value (Womack and Jones 1996). Lean concepts include creating value from the customer's perspective; to identify all the steps across the whole value stream; to make actions that create value flow; to only make what is pulled by the customer Just-In-Time; and to strive for perfection by continually removing successive layers of waste.

Customers exist in the System at many levels. There are the final customers, the users of the hospital and the owner who will operate it who had the facility handed over on time and on budget. The commissioning team (the customer of onsite assembly) had the M&E systems completed on time to be able to set them to work properly and with the right time to do this. Each of the trade teams in the onsite assembly phase (each the customer of the previous step in the assembly process) had space, materials, information, equipment and previous work when they needed it in order to carry out their own work uninterrupted in a safe and effective manner.

Customer value (from their perspective) has been created in the System, as far as has been possible, by reducing the non-added value wasteful activities that were revealed during the research steps. The steps in the value stream were identified in the projects value chain with each of the incremental actions within each step delivering value to each respective customer. Flow was created by allowing work to be undertaken free from disruption by others, with teams flowing from one construction zone to another using the Week-Beat method without delay. This pulled materials, information and equipment Just-In-Time to match this flow. Perfection has been pursued by recognising breakdowns in the System during weekly work plan meetings with action being taken to take account of and remedy these breakdowns.

5.3 CONTRIBUTION TO EXISTING THEORY AND PRACTICE

According to Arbulu and Zabelle (2006), organisations all over the world have been looking for ways to increase competitive advantage for the delivery of capital projects through the application of Lean concepts and techniques. Arbulu and Zabelle report that some organisations have achieved pockets of excellence and others have simply failed but truly competitive advantage has not yet been achieved. This research project has followed the methodology recommended by Arbulu and Zabelle by adopting a narrow and deep approach and, by ensuring with CHt's top management support, that all of the conditions for success were enabled. It has taken a holistic view to bring together manufacturing methods and techniques to design a Construction System to overcome the issues, or problems, that CHt faces in the UK M&E construction industry.

The research has achieved two levels of innovation, one at a process level and one at a product level. The process innovation is the development and successful implementation of the Construction System, which is a combination of methods acting together as an antidote to the research problem. The product innovation is the development of the innovative method for assembling, transporting and installing frameless M&E modules (the ATIF), whereby modularisation can be achieved with or without an offsite manufacturing capability.

As such, a whole system has been designed implementing a major number of Lean and agile manufacturing methods for which no evidence has been found by the author that this has been done before in such a comprehensive way in construction, other than in pockets of excellence (Arbulu and Zabelle 2006). The findings from the case study, in the words of the Industrial Sponsor, are far exceeding the company's expectations of performance improvement and will provide the company with an increase in competitive advantage as a result.

The contribution to existing theory and practice is the combination of countermeasures described in this thesis that have been developed and incorporated into a wider Construction System, in the same way that manufacturing has used this strategy with great success.

This work is feeding into other ongoing research initiatives in Lean Construction which include research work at Loughborough University's Lean Construction Data Laboratory and the Lean Commercial Management in Construction Programme, both of which are IMCRC[43] funded projects. Also, Loughborough's Lean Construction taught module (module CVP053) includes work from this research which is being taught as industry best practice to new students.

5.3.1 Interest generated by the System

Since the emergence of these results, the author has been invited to present the findings of this research project at significant forums in the construction industry both in the UK and the USA, these include:

- Lean Construction Institute (USA) 10th annual Lean Construction Congress, Boulder City, Colorado, USA, held in October 2008;
- Lean Construction Institute (UK) Annual Summit, Birmingham, UK, held in November 2008;
- The Chartered Institute of Building Services Engineers National Conference, London, UK, held in April 2009.

43 Innovative Manufacturing and Construction Research Centre.

The presentations and subsequent discussions have been received extremely well and requests have been made for further information regarding the research which has been provided in order to contribute to, and pass on new knowledge.

Following the presentation to the 10th Annual Meeting of the Lean Construction Institute, feedback was that the report provoked a significant rethinking that is changing the design and installation of M&E modules in the United States and the application of this approach is under active consideration by 2 major mechanical contractors and three hospital construction programs in the USA. The ATIF's have also been used by CHt on a separate project at Birmingham International Airport therefore proving their suitability and adaptability across different project types.

The knowledge from this research project has been disseminated internationally to academia and industry through conferences, workshops, and journal papers. The methods developed in the research project have been accepted through the peer review process of three IGLC conferences and two journals including the American Society of Civil Engineers Journal, the Practice Periodical on Structural Design and Construction.

5.4 IMPLICATIONS / IMPACT ON THE SPONSOR COMPANY

The implications to the sponsor company were discussed following presentation of the case study findings to the Industrial Supervisor, CHt's Business Leader. According to the supervisor, the outcome of the research project has exceeded the expectations of the company and can be summarised at two levels which are company and customer level implications.

5.4.1 Company level implications

Firstly, the Construction System will reinforce the Incident and Injury Free culture within the company; this is because it focuses on the workers wellbeing, health and safety and is facilitated by safer, more effective and productive work.

From a pure cost saving perspective, if for example the Construction System is embedded and repeatable across all of its projects, every one percentage point saved in labour spend reveals a cost reduction of £802,700[44] (financial year 2007 / 2008). For the financial year 2008 / 2009, a £1,002,800 cost reduction could have been achieved. This is presented in table 5.1. Multiply this by a factor of seven if the case study findings, a 7% labour cost reduction, were repeatable across all projects (this includes the labour element within the company's sub-contractors).

Table 5.1 Analysis of potential labour cost reduction (values are £millions)

Financial year	Annual turnover	Direct labour content at 23%	Value of each 1% saving in labour cost
2007 / 2008	£349	£80.27	£0.8027
2008 / 2009	£436	£100.28	£1.0028

In Ohno (2001) it is said that Toyota (and people involved in industrial engineering) use the thinking behind the formula:

Price – Cost = Profit

Toyota thinks "How can we reduce cost?" Costs do not exist to be calculated but to be reduced. So the most important issue, Ohno states, is to try various methods to see which ones reduce cost and which ones do not. On this basis, and especially in this time of global

44 One percent of CHt's labour spend as described in chapter 1 of this thesis.

recession, CHt can maintain competitiveness with reduced prices by reducing costs in a structured, confident manner (as opposed to pure cost cutting) using the competitive advantage that the Construction System offers.

Furthermore, it is the view of the Industrial Supervisor that given the findings that this research project has revealed, and should this be embedded and repeated across all of CHt's projects, that this would reduce the organisations operational risk profile thereby enhancing its enterprise value (explained earlier in this thesis). This is because the investment market considers construction risky so by applying the Construction System across all its projects, the company will have more predictable operational performance leading to more predictable revenue streams. This in turn means higher predictability of earnings therefore higher investor confidence. This is supported by DETR (1998) who report that the under-achievement of construction is graphically demonstrated by the City's view of the construction industry as a poor investment. It reports that the City regards construction as an industry that is unpredictable, competitive on price not quality and with too few barriers to entry for poor performers. With few exceptions investors cannot indentify brands among companies to which they can attach future value and as a result there are few loyal, strategic long-term shareholders in quoted construction companies. The report states that discussions with City analysts suggest that effective barriers to entry in the construction industry, together with structural changes that differentiated brands and improved companies' "quality of earnings" (i.e. stability of margins), could result in higher share prices and more strategic shareholders. It is believed, the report states, that such a change towards stability of profit margins would be at least as highly valued by the City as a simple increase in margins.

Other project cost benefits are reduced risk contingencies and preliminaries. Risk contingencies are built into project costs to cover the probability of cost overruns in accordance with risk assessments carried out at tender stage and part of this is for labour cost escalation. If projects can be delivered without overspending on labour then the associated risk contingency can be saved, or even eliminated, when confidence in the System is established over time. Costs for preliminaries can also be reduced should the System result in shorter construction cycle times. Again these costs can be saved at a project level or reduced over time as confidence is established in the System.

5.4.2 Customer level implications

According to Hawkins (1997), maximising the output on site is essential in order to increase a contractor's performance and the value for money investment of the customer. On this point, the Industrial Supervisor sees the Construction System delivering improved customer satisfaction, if for no other reason than providing certainty of time, cost and quality of its delivered projects. If construction cycle time is reduced and the built facilities are available earlier for end-user occupation, and dependant upon the facility, then revenue streams may be available earlier for the customer. Another customer level implication relates to relational forms of contract such as target cost projects, or pain/gain share contract forms (or similar). The potential savings generated within the project can then be shared between the customer and the contractor, to both their mutual benefit.

5.4.3 Sponsor company implications / impact summary

The Construction System has been shown to be successful following its implementation on the case study project. The System, the author confirms, is repeatable across CHt's project portfolio but with adaption to suit the particular project characteristics. It will mean investment in training and development of people and equipment, to allow the adoption of this new method or working, otherwise constraints and barriers will continue to exist.

The narrow and deep approach to implementation needs to be adopted, one project at a time, until all projects operate to the new business model. Teams to manage these future projects will need to be facilitated, individuals will need to be trained and mangers will need to be coached. These teams are composed of individuals, and these individuals are the ones who could potentially resist the change. Change can occur quite rapidly but adjusting to the change can often take time and effort (Arbulu and Zabelle 2006). In addition, further investment will be required to procure and develop equipment needed for the mobile work cells and parts centres for example, and then to manage and maintain these. This is an investment cost for the further development and upkeep of the System that CHt does not have at this time.

These potential constraints and barriers are therefore people, culture and change; lack of investment for training and development of people and the lack of investment for the development and maintenance of the System for wider adoption within CHt. Such constraints and barriers need to be acknowledged by CHt to be able to successfully diffuse the System across the wider business. Knowledge transfer mechanisms are also required to aid the diffusion and this will require CHt to produce new standard operating procedures within its quality management system. To take advantage of the benefits for wider adoption within the business, CHt will have to develop metrics to measure the diffusion of the System within the company. In the opinion of the author, metrics are required to measure if the five elements for successful implementation are in place for each new project in the roll-out of the narrow and deep approach (Arbulu and Zabelle 2006). These elements are:

1 The vision;

2 The skills needed;

3 The incentive needed;

4 The resources needed;

5 The action plan needed.

Without these metrics, and therefore the elements required for successful implementation, the implementation effort will most likely fail both within CHt and in the wider industry. CHt also need to develop a productivity measurement system as they do not have this at the time of completing this research project. They can however use the methods developed in the Construction System as a basis for one, combined with the findings achieved to act as benchmarks for measurement of success.

As well as this, new methods of estimating future bids will be required in order to build-in the competitive advantage that the Construction System offers to win new work and this needs to be developed in the near future by CHt.

Finally, in the same way that Toyota has developed a source of competitive advantage with the Toyota Production System, CHt are in a position to enhance their reputation within the industry, similarly leading to the System being a source of competitive advantage for them.

5.5 IMPLICATIONS / IMPACT ON WIDER INDUSTRY

As has been shown, the Construction System is a set of countermeasures to overcome the problems that M&E companies face today in construction. Whilst the System is developed for CHt, it can, with local adaption, be transferrable and successful within the wider industry. If nothing else, from a health and safety perspective, the industry should use some, if not all of the countermeasures described in this thesis. If just providing clear space, a good working environment, good ergonomics and everything the worker needs, contributes to their wellbeing and health and safety, then we have done our job to help reduce workers exposure to injury from either health or safety factors as a result of working in the construction industry. Just by providing workers a workbench (BSRIA best practice no. 62), which results in them not having to kneel or work on the floor, will help reduce the problems that cause injury. Plus of course improving productivity in an industry where this has traditionally been poor thus leading to changing the poor performance of construction, as reported in this thesis. Finally though, in the same way that barriers and constraints exist to the wider adoption of the System within CHt, these will also exist within the wider industry and the industry therefore needs to take due cognisance of these barriers, as does CHt.

5.6 RECOMMENDATIONS FOR INDUSTRY / FURTHER RESEARCH

Further research is recommended by the author in order to build upon and improve the Construction System to the benefit of CHt and the wider industry. These recommendations are drawn from the findings and implications of this research project, and are meant to further develop the System with more research that has fallen outside the scope of this project or became evident from the process undertaken. Further research recommended by the author is as follows:

- Knowledge transfer mechanisms between projects (repeatability of the System on varying project types);
- Development of a productivity measurement system;
- Development of metrics to measure the diffusion of the research findings within the company and the wider industry;
- Estimating for higher productivity and reduced project cycle-times to build-in the competitive advantage into new bids;

- Implications on the worker in terms of motivation, de-skilling or re-skilling (the dark side of Lean; or otherwise);
- Health impacts of the Construction System on the worker;
- Error proofing work to reduce human error in M&E manual work;
- Combining of location based scheduling with the capability of 4D CAD which would help to visually display the Week-Beat strategy.

5.7 CRITICAL EVALUATION OF THE RESEARCH

The most important critical evaluation of this research project concerns its implementation. Had the thesis author not been the Project Leader then would the Construction System have been so successful? In other words, had the author been a pure researcher imposed onto the project by CHt, would a traditionally thinking team accept the imposition of new thinking? This point strongly reinforces Arbulu and Zabelle (2006) conditions for success as described in chapter 3. Notwithstanding this, the implementation of the Construction System was successful and proves what can be done when deliberate interventions are made to overcome the problems that the construction industry faces. The recommendation for those implementing change, is to ensure that these conditions are in place for any change programme to be implemented successfully.

This research project designed and implemented the Construction System on the case study project which is a new-build hospital facility. The System can be adapted for other facilities which will have different construction characteristics and different M&E systems. The author believes that this is possible using the underpinning methodologies outlined in this thesis. Sequences between installation teams, types of modules, workplace equipment etc. merely need to be modified to suit to the actual characteristics of the particular project being undertaken.

5.8 CHAPTER SUMMARY

The M&E construction industry (and construction generally) has been shown to have historically poor health, safety and productivity performance and these problems face the sponsor company, CHt and others within the industry. The research presented in this thesis has developed a Lean and agile Construction System to overcome these problems and has implemented this on a complex M&E case study project in the healthcare sector of UK construction. With the support from Crown House Technologies and Loughborough University, the research has achieved the proposed aim and objectives. The System has been shown to be successful in its implementation, has made a positive impact on the sponsor company and has the potential to be implemented in the wider industry.

Finally, readers of this thesis and those wishing to embark on doing things differently and to move away from current practice and knowledge, are reminded of the following phrase…

"If you always do what you always did, then you'll always get what you always got…"

CHAPTER 6 REFERENCES

Abdelhamid, T. S., and Everett, J. G. (1999). Physiological demands of concrete slab placing and finishing work. Journal of Construction Engineering and Management, ASCE, 125(1), 47-52.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R., (2002). Representing work spaces generically in construction method models. J. Constr. Eng. Manage., 128(4), 296-305.

Akinci, B., Fischer, M., Kunz, J., (2002a). Automated generation of work spaces required by construction activities. J. Constr. Eng. Manage., 128(4), 306-315.

Arbulu, R., and Zabelle, T., (2006). Implementing Lean in construction: how to succeed. Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.

Ballard, G., (2000). The Last Planner System of production control. PhD thesis, Department of Civil Engineering, University of Birmingham, Birmingham, UK.

Ballard, G. and Matthews, O., (2004). Championship – prefabrication and assembly. Proceedings of the 12th annual conference of the International Group for Lean Construction, Elsinore, Denmark, August 3-5, 2004.

Bertelsen, S., Koskela, L., Henrich, G., and Rooke, J. (2006). Critical flow-towards a construction flow theory. Proc., Fourteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-14), Santiago, Chile, 31-40.

Burbidge, J.L., (1996). Period flow control. Clarendon Press, USA.

Bridger, R. S., (2003). Introduction to ergonomics. Taylor and Francis, New York, USA.

Cassell, C., and Symon, G., (2004). Essential guide to qualitative methods in organisational research. SAGE publications, UK.

Checkland, P., and Scholes, J., (1992). Soft systems methodology in action. Wiley Publications, UK.

Churcher, D., (2009). A design framework for building services 2nd edition, BSRIA technical note BG 6/2009, The Building Services Research and Information Association, Bracknell, UK.

Coghlan, D. and Brannick, T., (2003). Doing action research in your own organisation. SAGE publications, UK.

Colledge, B., (2005). Relational contracting – creating value beyond the project. Lean Construction Journal, Vol. 2 #1 April 2005.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2006). Design of a Lean and agile Construction System for a large and complex mechanical and electrical project. Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2007). Transforming traditional construction into a modern process of assembly using Construction Physics. Proceedings of the 15th annual conference of the International Group for Lean Construction, East Lansing, USA, 2007.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D. (2008). Modular assembly in healthcare construction – A mechanical and electrical case study. Proceedings of the 16th annual conference of the International Group for Lean Construction, Manchester, United Kingdom, 521-531.

Court, P., Pasquire, C., Gibb, A.G.F., (2009). Modular assembly with postponement to improve health, safety and productivity in construction. J. Practice Periodical on Structural Design and Construction. 14(2), 81-89.

Court, P., Pasquire, C., Gibb, A.G.F., (2009a). A Lean and agile Construction System as a set of countermeasures to improve health, safety and productivity in mechanical and electrical construction. Lean Construction Journal, November 2009.

DETR (1998), Rethinking construction, Department of the Environment, Transportation and the Regions, London, UK.

Deming, W. E., (1986). Out of the crisis. MIT Centre for Advanced Engineering Study.

Dicks, M., (2002). Commissioning management - how to achieve a fully-functioning building. BSRIA application guide 5/2002. ISBN 0 86022 599-2.

Everett, J. G. (1999). Overexertion injuries in construction. Journal of Construction Engineering and Management, ASCE, 125(2), 109-114.

Fellows, R. F., and Liu, A. M. M., (2003), Research methods for construction. Blackwell Publishing, Oxford, UK.

Forza, C. (1996). Work organisation in Lean production and traditional plants – what are the differences? Int. J. of Ops. Manage., Vol. 16. No. 2, 1996, 42-62.

Fredriksson, P., (2006). Mechanisms and rationales for the coordination of a modular assembly system – The case of Volvo cars. International Journal of Operations and production Management, Vol 26 No. 4 pp 350-370.

Gibb, A.G.F., (2006) (Keynote). Occupational health: slow accidents need solutions fast, in Fang, Choudry & Hinze (eds), Global Unity for Safety & Health in Construction, Proc. of CIBW99 Int. Conf., June 2006, Beijing, Tsinghua University Press, pp. 22-33.

Granath, J.A., (1998). Torlanda to Uddevalla via Kalmar: a journey in production practice in Volvo. Seminário Internacional Reestruturaçã Productiva, Flexibilidade do Trabalho e Novas Competências Profissionais COPPE/UFRJ, Rio de Janeiro, Brasil.

Green, A., (1999). The dark side of Lean Construction: exploitation and ideology. Proc., Seventh Annual Conf. of the Int. Group for Lean Construction (IGLC-7), Berkeley, California, 1999.

Goldratt, E. M., and Cox, J., (2004), “The goal: a process of ongoing improvement.” Gower Publishing, Aldershot, UK.

Goodier, C.I., Gibb, A.G.F., (2005). Barriers and opportunities for offsite in the UK. Systematic innovation in the management of projects and processes. Abdul Samad Kazi (ed), cib Helsinki international joint symposium, pp. 148-158, ISBN 952 5004 64 3.

Guo, S. J., (2002). Identification and resolution of work space conflicts in building construction. J. Constr. Eng. Manage., 128(4), 287-295.

Hanna, A. S., Peterson, P., and Lee, M-J., (2002). Benchmarking productivity indicators for electrical/mechanical projects. J. Constr. Eng. Manage., 128(4), 331-337.

Hawkins, G., (1997). Improving M&E site productivity, BSRIA technical note TN 14/97, The Building Services Research and Information Association, Bracknell, UK.

Hawkins, G., (2002). Site productivity – 2002. A guide to the uptake of improvements, BSRIA technical note TN 13/2002, The Building Services Research and Information Association, Bracknell, UK.

Health and Safety Executive, (2000). Backs for the future: safe manual handling in construction, HSE books, Norwich, UK.

Health and Safety Executive, (2003). Understanding ergonomics at work: reduce accidents and ill health and increase productivity by fitting the task to the worker, HSE Books, 2003.

Health and Safety Executive, (2007). Health and safety in the construction industry. <http://www.hse.gov.uk/construction/index.htm> (Mar. 4, 2007)

Health and Safety Executive, (2007a). Better backs in construction. <http://www.hse.gov.uk/construction/backs/index.htm> (Mar. 4, 2007).

Health and Safety Executive, (2007b). Musculoskeletal disorders – HSE and MSD's. <http://www.hse.gov.uk/msd/hsemsd.htm> (Mar. 4, 2007).

Henrich, G., Tilley, P., Koskela, L., (2005). Context of production control in construction. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia.

Hopp, W. J., and Spearman, M. L. (2001). The MRP crusade. Factory physics, 2nd Ed., Irwin/McGraw-Hill, New York, USA, 109-150.

Horman, M. J., Orosz, M. P., and Riley, D. R. (2006). Sequence planning for electrical construction. J. Constr. Eng. Manage., 132(4), 363-372.

Howell, G., (1999). What is Lean Construction, Proc. Seventh Annual Conf. of the Int. Group for Lean Construction (IGLC-7), Berkeley, California, 1999.

Howell, G., Laufer, A., and Ballard, G. (1993). Interaction between subcycles – one key to improved methods. J. Constr. Eng. Manage., 119(4), 714-728.

Howell, G., and Ballard, G. (1999). Bringing light to the dark side of Lean construction: a response to Stuart Green. Proc., Seventh Annual Conf. of the Int. Group for Lean Construction (IGLC-7), Berkeley, California, 1999.

Howell, G., and Ballard, G. (1999a). The design of construction operations. LCI white paper-4. Lean Construction Institute Implementation Workshop, Portland, Oregon, 1999.

Jongeling, R., and Olofsson, T., (2007). A method of planning for work-flow by combined use of location based scheduling and 4D CAD. Automation in Construction, volume 16, issue 2, March 2007, pp. 189-198.

Jorgensen, B., and Emmitt, S., (2008). Lost in transition: the transfer of Lean manufacturing to construction. Engineering, Construction and Architectural Management, Vol. 15 No. 4, 2008, pp. 383-398.

Kivi, P., and Mattila, M. (1991). Analysis and improvement of work postures in the building industry: application of the OWAS method. Applied Ergonomics, 22(1): 43-48.

Koningsveld, E. A. P. and Van Der Molen, H. F. (1997), History and future of ergonomics in building and construction. Ergonomics, 1997, vol. 40, no.10, 1025-1034.

Koskela, L., (2004). Moving on – beyond Lean Thinking. Lean Construction Journal, Vol. 1 #1 October 2004.

Koskela, L., (2004a). Making-do – the eighth category of waste. Proceedings of the 12th annual conference of the International Group for Lean Construction, Elsinore, Denmark, August 3-5, 2004.

Larsen, J., Odgaard, G., and Buch, S., (2003). A trade union's view of the building process. Proceedings of the 11th annual conference of the International Group for Lean Construction, Blacksburg, Virginia, July 22-24, 2003.

Latham, M., (2004). Constructing the team, joint review of procurement and contractual arrangements in the UK construction industry. HMSO, London, 1994.

Lean Construction Institute (2009): What is Lean Construction? < http://www.Leanconstruction.org/>, (Jan. 5, 2009).

Lean Enterprise Institute (2003). Lean lexicon – a graphical glossary for Lean thinkers. The Lean Enterprise Institute, Massachusetts, USA.

Liker, J. K. (2004). The Toyota way: 14 management principles from the world's greatest manufacturer, McGraw-Hill, New York, USA.

Luckins, (2003). Mechanical installation times guide for estimators. Trade Services Information Limited, 2003, England.

Luckins, (2003). Electrical installation times guide for estimators. Trade Services Information Limited, 2003, England. ISBN 0 5912985 3 4.

Maslow, A. H., (1943). Theory of human motivation, Psychological Review, 50, 370-396.

Mason-Jones, R., Naylor, B., and Towell, D., (2000). Engineering the leagile supply chain. International Journal of Agile Management Systems, 2/1, 54-61.

Mawdesley, M.J., and Long, G., (2002). Prefabrication for Lean building services distribution. Proc. Tenth Annual Conf. of the Int. Group for Lean Construction (IGLC-10), Gramado, Brazil.

McNamara, Brian E., (1986). Ergonomics: Maximising the human resource. Logistex Forum, May 6-8, 1986.

Naylor, J. B., Naim, M. M., and Berry, D., (1999). Leagility: integrating the Lean and agile manufacturing paradigms in the total supply chain. International Journal of Production Economics (1999), No. 62, pp. 107-18.

Ohno, T., (1988). Toyota Production System, beyond large scale production. Productivity Press, USA.

Parsloe, C. J., (1997). Allocation of design responsibilities for building services engineering, BSRIA technical note TN 21/97, The Building Services Research and Information Association, Bracknell, UK.

Pasquire, C.L., and Connolly, G.E., (2002). Leaner construction through off-site manufacturing. Proc. Tenth Annual Conf. of the Int. Group for Lean Construction (IGLC-10), Gramado, Brazil.

Pasquire, C.L., and Connolly, G.E., (2003). Design for manufacture and assembly. Proc. Eleventh Annual Conf. of the International Group for Lean Construction (IGLC-11), Blacksburg, Virginia.

Pasquire, C., Gibb, A.G.F., and Blissmass, N., (2005). What should you really measure if you want to compare prefabrication with traditional construction? Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

Porter, M. E., (1985). Competitive advantage. Simon and Schuster, New York, USA.

Rother, M., and Harris, R., (2001). Creating continuous flow – an action guide for managers, engineers and production associates. The Lean Enterprise Institute, Massachusetts, USA.

Sillanpaa, J., Lappalainen, J., Kaukiainen, A., Viljanen, M., Laippala, P., (1999). Decreasing the physical workload of construction work with the use of four auxiliary handling devices. International Journal of Industrial Ergonomics, no.24, 1999, 211-222.

Skipworth, H., and Harrison, A., (2004). Implications of form postponement to manufacturing: a case study. Int. J. Prod. res., 15 May 2004, vol. 42, no. 10, 2063-2081.

Smith, E, E., Nolen- Hoeksema, S., Fredrickson, B. L., and Loftus, G. R., (2003). Atkinson and Hilgard's introduction to psychology. Wadsworth/Thomson Learning, Belmont, USA.

Sporrong, H., Sandsjo, L., Kadefors, R., Herberts, P., (1999). Assessment of workload and arm position during different work Sequences: a study with portable devices on construction workers. Applied Ergonomics, no.30, 1999, 495-503.

The Chartered Institute of Building Services Engineers. (2003). Commissioning management – CIBSE commissioning code M: 2003. The Chartered Institute of Building Services Engineers, London, UK.

The Productivity Press Development Team (2002). Standard work for the shopfloor. Productivity Press, USA.

Thomas, H. R., Horman, M. J., and de Souza, U. E. L., (2004). "Symbiotic crew relationships and labor flow." J. Constr. Eng. Manage., 130(6), 908-917.

Ulrich, K. T., Eppinger, S. D. (2004). Product design and development, 3rd Ed., McGraw Hill, New York, USA, 163-186.

Wilson, D., (2000). Innovative M&E installation, BSRIA ACT 9/2000, The Building Services Research and Information Association, Bracknell, UK.

Winch, G. M., and North, S., (2006). Critical space analysis. J. Constr. Eng. Manage., 132(5), 473-481.

Womack, J.P. and Jones, D.T., (1996). Lean Thinking, banish waste and create wealth in your organisation. Simon and Schuster, UK.

Yang, B., and Burns, N. (2003). Implications of postponement for the supply chain. Int. J. Prod. res., 2003, vol. 41, no. 9, 2075-2090.

Yin, R. K., (2003), Case Study Research: Design and Methods. SAGE Publications, USA.

APPENDICES

Appendix A: Paper 1 (refereed, conference)

Appendix B: Paper 2 (refereed, conference)

Appendix C: Paper 3 (journal, published)

Appendix D: Paper 5 (refereed, conference)

Appendix E: Paper 5 (journal, published)

Appendix F: BSRIA best practice recommendations

Appendix G: Safety results from the sample period

Appendix H: Lessons learned from implementation

APPENDIX A PAPER 1 (REFEREED, CONFERENCE)

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

LEAN AS AN ANTIDOTE TO LABOUR COST ESCALATION ON COMPLEX MECHANICAL AND ELECTRICAL PROJECTS.

Peter F. Court, Christine Pasquire, Alistair Gibb, David Bower

ABSTRACT

This paper represents "work-in-progress" as part of a collaborative research project being undertaken at the Centre for Innovative Construction Engineering for an Engineering Doctorate at Loughborough University, UK. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the company). The project will have specific objectives, which will be capable of making a significant contribution to the performance of the company. That is, the tasks will benefit the company whether or not the Engineering Doctorate was being undertaken. It will not be a "student" project, which has only been selected to keep the research engineer busy, nor will the tasks be at the margin of the company's interest.

In the mechanical and electrical (M&E) sector in the UK, labour cost is one of the largest variables which can have a direct influence on the financial outcome of a project. Actual labour cost incurred has a dependency upon the productivity achieved on site, which in turn is dependant upon the conditions that prevail on that site. For a major UK M&E contractor, labour cost has escalated to such an extent that margin slippage has occurred. Margin slippage can be defined as the negative variation between the expected margin (gross profit) for a project when acquired, and the final margin when the project is finished. Consequentially, the company, as part of a performance improvement initiative, have the

objective of developing Lean techniques to overcome the causes of the cost escalation – poor productivity, and see this research project and implementing Lean as a result of it, as a vehicle to deliver the improvement. This paper will propose that Lean techniques, when imposed upon a project, can be an antidote to the causes of poor productivity, and therefore prevent labour cost escalation, along with its impact on the project's final profitability. These Lean techniques, known as "interventions", are applied to a case study project with positive results in terms final labour cost and margin.

KEY WORDS

Lean Construction, margin slippage, productivity, labour, mechanical and electrical sector.

INTRODUCTION

This paper represents "work-in-progress" as part of a collaborative research project being undertaken at the Centre for Innovative Construction Engineering for an Engineering Doctorate at Loughborough University, UK. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the company). The project will have specific objectives, which will be capable of making a significant contribution to the performance of the company. That is, the tasks will benefit the company whether or not the Engineering Doctorate was being undertaken. It will not be a "student" project, which has only been selected to keep the research engineer busy, nor will the tasks be at the margin of the company's interest.

The themes of the research project are "Innovative Construction Technologies" driven by the desire to use leading edge research and learning to improve the business of the sponsoring organisation. The sponsor company is a major provider of advanced mechanical, electrical and communications solutions in the construction sector in the UK. It works for customers in banking, retail, leisure and commercial property development, as well as education, health, defence and government offices, secure establishments and airports.

RESEARCH PROJECT OBJECTIVE

A primary objective of the company is to develop a way of working that will contribute to reducing the costs of implementing its projects by a target of 10%. This is being delivered as a performance improvement initiative, and there are four primary business drivers behind this objective, and these are; 1) client driver; clients want more and more for less and less; 2) competitiveness; the company operate in a competitive environment; 3) efficiency improvement; poor productivity is a feature of UK M&E projects, and; 4) competing new alternatives; whole buildings can be manufactured off site, and assembled on site, making large sections of traditional site installation redundant.

It is not the intention to explore these drivers further here, but they are the reasons for the improvement initiative, however, Gibb and Isack (2003) explains more on client expectations and drivers. Of particular concern within the company are poor labour productivity and the resultant cost escalation it has experienced on its recent major projects. This has had serious consequences on the financial performance of the projects to the point where severe margin slippage has occurred. Margin slippage can be defined as the negative variation between the expected margin (gross profit) for a project when acquired, and the final margin when the project is finished.

On these particular projects, these being the worst case and having the most serious affect on the company, labour cost escalation has been vast. This is presented in table 1 below. The company reports that not all of the losses are entirely attributed to poor productivity, but it is the main contributing factor. Other cost variables are worthy of attention, but are not the focus of this paper. What the company intend to do is to develop new ways of working to overcome the causes of poor productivity, and see the research project, and implementing Lean as a result of this, as a vehicle to deliver its improvement objectives. Productivity improvement interventions will be designed using “Lean Thinking” principles, and applied to a case study project, as will be shown. The company further intend to implement these, and further Lean techniques into what will be called their “Lean Construction System”, to be applied to all projects as they occur over time. So the interventions implemented as part of this research are only aspects of the “whole” system to be developed.

DOES LABOUR HOLD THE KEY?

According to Hawkins (1997), labour costs typically constitute 30% of the overall project M&E costs, so maximising the output on site is essential to increase a contractor’s performance and the value for money investment of the customer. This statement was part of report of an investigative study, undertaken by the Building Services Research and Information Association (BSRIA), and sets a foundation for understanding the problems and issues that the UK M&E industry faces within the construction sector. BSRIA undertook this investigative study comparing 4 UK, 1 American, 1 German and 1 Swedish construction project to highlight productivity problems relating to M&E building services, to assist the UK M&E industry in promoting improvements in productivity, and to suggest remedies to solve these problems and improve performance. Remedies are indeed suggested in the form of best practice recommendations, but actual design and implementation of these remains at the discretion of the contractor.

Within the company, as previously mentioned, the increased cost of labour on recently completed major projects has had a direct impact on the financial outcome of those projects, and because of the scale of the cost overruns, the company itself. This is shown in table 1.

These projects were run in a traditional manner, with no specific Lean interventions being made.

Table 1 Labour cost escalation and margin slippage on recently completed major M&E projects with high complexity and high value (values are £000's). Project 1 was not a project of the company but has been included here as a comparator of performance

Cost Element	Project 1	Project 2	Project 3
Project value	£19,096	£42,665	£38,500
Estimated labour cost (A)	£1,117	£6,408	£5,295
Final labour cost (B)	£4,052	£12,088	£22,962
Labour cost escalation (B-A)	£2,935	£5,680	£17,667
Estimated margin (C)	£2,334	£4,169	£1,381
Final margin at completion (D)	£319	-£4,773	-£16,255
Margin slippage (C-D)	£2,015	£8,942	£17,636

It can be seen that each project saw an increase in labour costs of 263%, 89% and 334% respectively. Whilst other cost variables on the projects influenced the final margin, the losses on labour virtually equalled the margin slippage suffered.

SITE FIRST PRINCIPLE

In his book, Toyota Production System, Ohno (1988) describes his plant-first principle. He says that the production plant is manufacturing's major source of information, and that it provides the most direct, current, and stimulating information about management. This is the same for the construction site; the site is to construction what the plant is to manufacturing. It is the culmination of all the construction processes and what is given to the customer when it is finished. Also, are workers the only participants in the building process *directly* generating value to the customer? Larsen, Odgaard and Buch (2003) argue this point, and these are the reasons for the principle themes of this project. It seeks to focus on the worker, the worker's environment, and what makes the worker do what they do and why they do it, and will only be concerned with M&E workers and those of key interfacing trades insofar as they apply. The overarching aim then is to implement "Lean" in an action research project for the company with a particular focus on the worker and their activities and behaviour. This will be addressed through investigating three principal themes:

Practical: (sensible, useful, effective, involving, the simple basics) ***What*** *people "do" at the workplace* – Standardisation of work, process and products to create flow, pull and value delivery. This aspect of the research will seek to develop innovative methods and use of innovative components for installation by standardising the work. Standard work is an agreed-upon set of work procedures that establishes the best and most reliable methods and sequences for each process and each worker (Productivity Press, 2002).

Physical: (to do with the body as opposed to the mind or spirit) ***How*** *people do things in the workplace* – Ergonomics and workplace organisation to improve health, safety and productivity. This aspect of the research will seek to address how people do things in the workplace. Of particular interest is ergonomics, which in the industrial workplace is generally defined as a variation of the following:

"A science devoted to determining the range of anatomical, physiological and psychological human factors and designing work environments conducive to these ranges with the objective of maximising productivity and minimising injury" (McNamara, 1986).

Psychological: (of or affecting the mind) ***Why*** *people do what they do* – Understanding motivation of the worker and its influence on behaviour at the workplace. This aspect of the research will separately look at the psychological and motivational factors that cause the worker to behave in the way they do.

SO WHAT'S THIS ABOUT AN ANTIDOTE?

As Womack and Jones, 1996, states, Lean Thinking is a powerful ***antidote*** to *muda*. *Muda* is a Japanese term for waste, and specifically any human activity, which absorbs resources but creates no value. These are; "Mistakes which require rectification, production of items no one wants so that inventories and goods pile up, processing steps which aren't needed, movement of employees and transport of goods, waiting for upstream activities, goods and services that the customer does not want."

Added to this is the eighth category of waste, making-do (Koskela 2004). Koskela contends that there is a very common, generic type of waste that should be added to the list, because it can be justified using the same conceptualisations as used by the seminal authors. Further, the principal problems described by Hawkins (1997), can each be categorised as one form of muda or another. He ultimately charges the UK M&E industry with very low productivity for a variety of reasons, as explained in his report. So herein lays the hypothesis of Lean as an antidote to labour cost escalation. This should be tested with a case study.

TURNING THEORY AND RESEARCH INTO ACTION – A CASE STUDY

An action research approach was chosen to understand where to start and what to do first. Coghlan and Brannick (2003), define action research as involving a cyclical process of diagnosing a change situation or problem, gathering data, taking action, and then fact finding about the results of that action in order to plan and take further action. Also, the key idea of action research is that it uses a scientific approach to study the resolution of important social and organisational issues together with those who experience these issues directly.

In order to commence the process of deciding where and how to start making changes to current practice, observational studies were undertaken on various sites of the company. A primary finding from this is that making-do, or improvisation[45] occurs naturally to a greater or lesser degree with regard to how physical work on site is carried out, and this seemed to have a direct influence on productivity itself. In order to formulate an understanding of this in the context of this case study, an ethnographic study was then undertaken. Ethnography is a style of research rather than a single method and uses a variety of techniques to collect data (Cassell and Symon 2004). They defined this style of research as:

"…the study of people in naturally occurring settings or 'fields' by means of methods which capture their social meanings and ordinary activities, involving the researcher participating directly in the setting, if not also in the activities, in order to collect data in a systematic manner but without meaning being imposed on them externally…"

The purpose of this study was for the researcher to become a participant in the site process in order to be immersed in the day-to-day site activities and not just be an observer. This study did not set out to measure specific productivity performance of the activities undertaken; enough of this has been done already (Hawkins, 1997). Rather, the primary objective was to experience the conditions that exist on site and occur naturally, and how workers do their work, without intervention. This method will allow the researcher to understand people's actions and their experiences of the world in natural settings as they occur independently of experimental manipulation (Cassell et al. 2004). One week was spent as a ductwork fitter's assistant (not a project for the company), and another week was spent as an electrician's

45 Improvisation is proposed here as a form of making-do. Making-do, according to Koskela (2004), is the eighth category of waste adding to the 7 wastes defined by Womack and Jones (1996). To improvise: to make, invent, or arrange offhand; to fabricate out of what is conveniently on hand (Merriam-Webster online dictionary).

assistant (this was a project of the company). This involved the researcher doing actual installation work with teams under the direction of the team leader. A diary was kept at the end of each day to record events and discussions and digital images were taken. A "rich picture" of the key words and phrases from the diary entries was created in order to reveal a rich moving pageant of relationships, which is a better means of recording relationships and connections than is linear prose (Checkland and Scholes, 1992).

The main findings are summarised as follows:

- Limited, unplanned or improvised workplace organisation, workbenches, and equipment;
- Assembly work carried out on the floor or on whatever came to hand;
- Materials stored randomly around the site in no particular order, and in unknown quantities (figure 4);
- Scaffold systems provided that had to be accessed, with no facilities to store materials or tools. If something was missing, the operative had to climb back down to replenish whatever was needed;
- Tools only provided by the tradesmen - they had what they had irrespective of their suitability;
- Various trades worked in the same area at the same time. Materials for one trade were left in the way of the other trade/trades.

The ethnographic studies revealed the amount of waste and improvisation that naturally occurs without attention being given to eliminating the causes of it. If Lean interventions are designed to overcome the causes of this waste, and this prevents labour costs from escalating, then Lean as an antidote can work.

The following images represent a sample of the research findings:

Figure 1 Improvised cable dispensing

Figure 2 Working on the floor

Figure 3 Conventional scaffolding and manual handling

Figure 4 Improvised workbench and random storage of components

Figure 5 Unplanned workplace, conventional scaffold

Figure 6 Various trades in same workplace, materials in each trades way

Given this data, the next phase was to design Lean interventions to be able to overcome the causes of waste, and then to further test them in a live situation. A project was chosen as the "experiment", and a hypothesis, which is a statement about cause and effect that can be tested, was set as follows:

"Lean As an Antidote to Labour Cost Escalation on Complex Mechanical and Electrical Projects"

Labour is the independent variable to be manipulated in the experiment, and the outturn cost of labour is the dependent variable, which is observed as the outcome of the experiment. In order to manipulate the independent variable, labour, Lean interventions were designed and applied to the project. These were standardisation of components, standardised work sequencing, mobile work cell and ergonomic access equipment. Each of these was designed to overcome the common route causes of the waste experienced during the ethnographic study. So let's look at each one in turn:

STANDARDISATION OF COMPONENTS

The report, Innovative M&E Installation (Wilson, 2000), follows on from BSRIA's Improving M&E Site Productivity (Hawkins, 1997). The research underlying this report led to the recommendations that alternative systems, components, materials and innovative methods should be thoroughly evaluated to identify opportunities for productivity gains on M&E projects. It concludes that the UK construction industry must replace outdated components and processes if it is to remain competitive in a global marketplace. This research project has found that the UK construction industry can realise a significant gain in installation performance through the adoption of innovative components and systems. Also, according to Ballard and Matthews (2004), a Lean ideal for the championship, prefabrication and assembly, is to "simplify site installation to final assembly and commissioning". These principles were considered in the context of this case study and the solutions were selected accordingly, and summarised in table 2.

Table 2 Solutions selected in accordance with installation activity and benefits derived from the solution (terminology for benefits is as used in Wilson (2000), Innovative M&E Installation)

Activity	Solution selected	Benefit of solution
Connection to the structure	Shot fixing system	Increased productivity
Method of support / suspension	Pre-assembled, integrated supports	Integrated system; increased productivity
Means of connecting service to support	Lightweight, fast assembly channel system; quick fit support components, pipe-clips etc.	Increased productivity; material savings; ease of installation
System installation	Press-fit pipework and conduit systems	Increased productivity; ease of installation
Tools and equipment	Cordless power tools; mobile work cell and ergonomic scaffold system	Increased productivity; improved working practices

The specific purpose of this intervention was to eliminate unnecessary site processing of materials and fittings.

STANDARDISED WORK SEQUENCING

A "Week-Beat" system of structuring the work was employed, where the building was divided into smaller work zones (approx 1,000m2) and sequenced a "parade of trades" through each zone. Each trade was provided a period of one week in each zone to complete their work. This is as described by Horman et al (2002) as short interval production scheduling (SIPS). The specific purpose of this intervention was to eliminate the situation whereby materials and access equipment for one trade interferes with another, and tradesmen are fighting for the same workplace.

MOBILE WORK CELL

Santos et al (2002) described applying the concept of mobile cell manufacturing in construction. This paper presents the results of an exploratory study investigating the application of the “mobile cell manufacturing” concept within the construction environment using a case study research method. The paper defines the characteristics of a cell as creating a work flow where tasks and those who perform them are closely connected in terms of time, space and information.

These were the basic ingredients in the design of a simple mobile work cell appropriate to M&E workers. These were designed in conjunction with the operatives with the objective of having all that was needed at hand when it was needed, with the ability to be mobile and be able to move around the product (the installation). The following equipment was developed and provided:

- Mobile MTS component trolley – see figure 7.
- Mobile cable dispensing and MTS component trolley – see figure 8.
- Mobile workbench with vice, shelf and drawers.
- Mobile material trolley for pipes and electrical containment.

Figure 7 Mobile component trolley, with simple manual replenishment

Figure 8 Mobile cable dispensing and component trolley with simple manual replenishment

The specific purpose of this intervention was to eliminate unnecessary sorting, fetching, looking, bending, carrying etc of materials and fittings necessary to carry out the work uninterrupted.

ERGONOMIC ACCESS EQUIPMENT

The majority of M&E equipment is installed at high level within buildings, and this requires the worker to gain access in order to install materials and components using access equipment. Normal scaffolding typically consists of standard sections assembled to provide the necessary working platform height with kickboards and handrails. Access to the platform is via an integral ladder normally accessed from the inside of the tower through a lift up hatch in the platform floor. Tools, materials, consumables etc. are placed on the platform floor and used from there. This is a time consuming process and involves the worker climbing, stooping, bending, twisting and reaching just to get to the place of work. In consideration of this, a more ergonomic scaffold was designed with the objective of minimising significant body motions when gaining access to and carrying out work at the point of installation (high level). This included getting from the floor, to the services installation point, and to the underside of the concrete slab for fixing supports, and the like. The tower is still assembled from standard sections but put together in a different way. It is readily accessible via a series of steps at one end to give access to the services working height, and a step-up "poop-deck" at the furthest end to provide higher access to the underside of the slab. On-board storage bins are provided which are refilled using a simple manual replenishment system (figures 9 and 10).

The specific purpose of this intervention was to eliminate unnecessary motions for the tradesman getting to the place of work, and to have the necessary materials and fittings at hand to carry out the work uninterrupted.

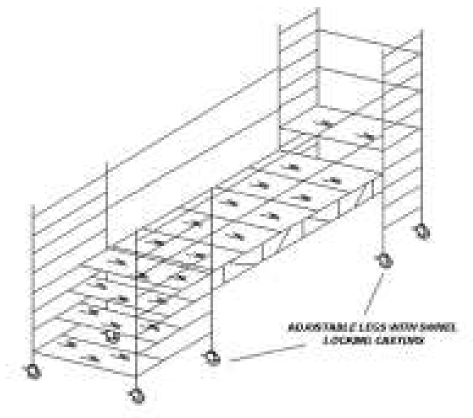

Figure 9 Tower as designed

Figure 10 Actual tower

RESULTS

This case study set out to measure the cost of labour used compared to the estimated labour cost, and consider its impact on the final margin of the project. To do this, actual labour used (not earned) was monitored on a weekly basis from the start of the project and compared to planned labour usage, and this is represented in figure 11.

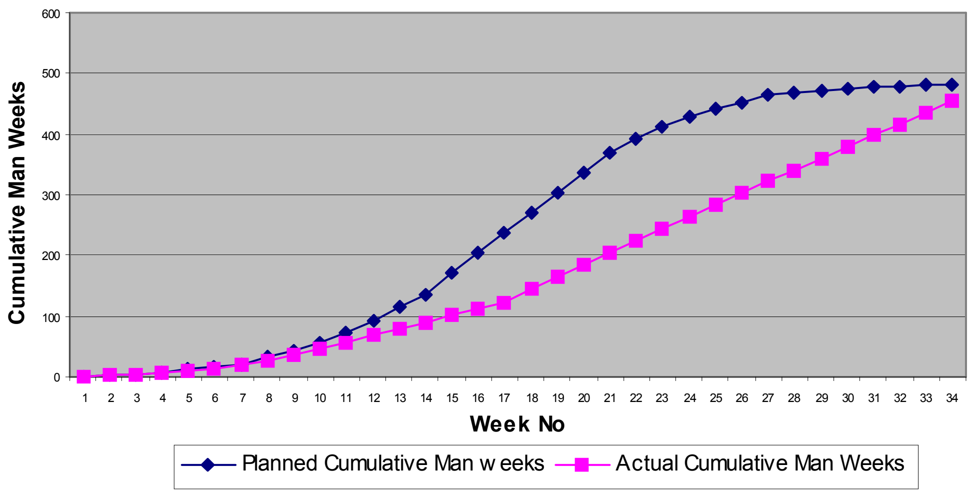

Figure 11 Planned cumulative man weeks versus actual cumulative man weeks

This study did not intend to measure specific enhancements to productivity such as metres of cable / pipe installed; rather, it sought in a fairly simple but scientific manner to test the effect that the Lean intervention inputs had on the cost of labour, on a weekly basis, then cumulatively. The authors do recognise, however, that the former would be valuable for future research to test the actual effectiveness of each of the interventions.

As can be seen, actual man weeks were consistently below planned on a week-by-week basis, with actual cumulative man weeks being 8.5% below that planned. Table 3 below represents the estimated costs for the project, showing each element, and comparing this to the final cost per element.

Table 3: Estimated costs per element compared to final costs per element (values are £000's)

Element	Estimated costs	Final costs	Variance	Variance %
Value	£1,672	£1,726	£54	3%
Costs:				
Materials and plant	£590	£550	-£40	-7%
Labour	£335	£309	-£26	-8%
Sub-Contract	£357	£375	£18	5%
Preliminaries	£181	£138	-£43	-24%
Contingency	£17	£17	Nil	Nil
Sub-Total Costs	£1,480	£1,389	-£91	-6%
Gross Margin Totals	£192	£337	£145	75%
Gross Margin / Revenue Ratio	11.5%	19.5%	8%	

A point to note is that the researcher did not influence the tradesmen by being present in the experiment, this did not occur. Once the interventions were made, progress was monitored by phone-calls and random site visits.

DISCUSSION

Table 3 shows that the project ended with a 7% saving in materials and plant, an 8% saving in labour, a 5% increase in sub-contract costs and a 24% saving in preliminaries. Overall the project had a cost saving of £91k, which resulted in a margin increase of £144k, contributed too also by an increase in value from the customer of £53K.

Under normal experimental conditions, it would have been desirable to compare these results with those of a control experiment, where the hypothesised cause was absent. In other words, to observe an exact same project that runs at exactly the same time but without the Lean interventions being made. However, in the context of operating in a live business and with a live project it was not possible to do so. The historic projects shown in table 1 represent the control group which did not have Lean interventions imposed upon them, the cause, but had the result of substantially increased labour costs, the effect, contributing to severe margin slippage. What this experiment has shown is that the four interventions proved effective in enhancing productivity, and the outcome in terms of reduced labour costs seems to be a function of these inputs. Did, therefore, these interventions eliminate the route causes of waste that would have otherwise occurred naturally? It would appear so. Labour costs did not escalate and margin slippage did not occur, in fact the margin increased significantly on the case study project.

It could be argued that the project improved its financial outcome because of skilled project management, a good estimate, a better client, or better contractors in the other trades etc. This cannot be substantiated in the context of this study. But given that the company has experienced increased labour costs where interventions were not made, the results of this experiment are an encouraging step in its performance improvement initiative, by showing positive results in its first endeavours. So, is “Lean” an antidote to labour cost escalation on complex M&E projects as hypothesised, and did this lead to preventing margin slippage? The authors would argue yes, it is, and yes, probably it did. They also recognise that other cost variables need to be controlled which deserve equal attention in the future. But the final reminder is that this research set out to focus on the labour element only, this being the company’s biggest current concern. This research has investigated the practical and physical themes of the overall research project. The psychological theme, although partly experienced during the ethnographic study, was not investigated.

FURTHER RESEARCH

These interventions were the first stage of designing and implementing a Lean Construction System for the company. The findings from this report will be used to inform and develop standardised operating procedures and routines for how work will be conducted in the future on new projects. This will be together with new Lean features yet to be researched, developed, implemented and tested on these new projects, which will be reported on in the future. One aspect of this will be psychological factors that influence the worker. This was not considered as part of this case study, but is one of the main themes for the research project.

REFERENCES

Ballard, G. and Matthews, O., (2004). Championship – prefabrication and assembly. Proceedings of the 12th annual conference of the International Group for Lean Construction, Elsinore, Denmark, August 3-5, 2004.

Cassell, C. and Symon, G., (2004). Essential guide to qualitative methods in organisational research. SAGE publications.

Checkland, P. and Scholes, J., (1992). Soft systems methodology in action. Wiley Publications, UK.

Coghlan, D. and Brannick, T., (2003). Doing action research in your own organisation. SAGE publications, UK.

Gibb, A.G.F. and Isack, F. (2003). Re-engineering through pre-assembly: client expectations and drivers. Building Research and Information, 31 (2), 146-160.

Hawkins, G., (1997). Improving M&E site productivity, BSRIA technical note TN 14/97, The Building Services Research and Information Association, Bracknell, UK.

Horman, M.J., Messner, J.I., Riley, D.R., Pulaski, M.H., (2003). Using buffers to manage production: a case study of the pentagon renovation project. Proceedings of the 11th annual conference of the International Group for Lean Construction, Blacksburg, Virginia, July 22-24, 2003.

Koskela, L., (2004). Making-do – the eighth category of waste. Proceedings of the 12th annual conference of the International Group for Lean Construction, Elsinore, Denmark, August 3-5, 2004.

Larsen, J., Odgaard, G., and Buch, S., (2003). A trade union's view of the building process. Proceedings of the 11th annual conference of the International Group for Lean Construction, Blacksburg, Virginia, July 22-24, 2003.

McNamara, Brian E (1986). Ergonomics: maximising the human resource. 1986 Logistex Forum, May 6-8, 1986.

Ohno, T., (1988). Toyota Production System, beyond large scale production. Productivity Press, USA.

Santos, A., Moser, L., Tookey, J., (2002). Applying the concept of mobile cell manufacturing on the drywall process. Proceedings of the 10th annual conference of the International Group for Lean Construction, Gramado, Brazil.

The Productivity Press Development team (2002). Standard work for the shopfloor. Productivity Press.

Wilson, D., (2000). Innovative M&E installation, BSRIA ACT 9/2000, The Building Services Research and Information Association, Bracknell, UK.

Womack, J.P. and Jones, D.T., (1996). Lean Thinking, banish waste and create wealth in your organisation. Simon and Schuster, UK.

APPENDIX B PAPER 2 (REFEREED, CONFERENCE)

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2006). "Design of a Lean and Agile Construction System for a Large and Complex Mechanical and Electrical Project." Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.

DESIGN OF A LEAN AND AGILE CONSTRUCTION SYSTEM FOR A LARGE AND COMPLEX MECHANICAL AND ELECTRICAL PROJECT

Peter Court, Christine Pasquire, Alistair Gibb, David Bower

ABSTRACT

This paper represents "work-in-progress" as part of a collaborative research project being undertaken at the Centre for Innovative Collaborative Engineering for an Engineering Doctorate at Loughborough University, UK. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the sponsor company). The project will have specific objectives, which will be capable of making a significant contribution to the performance of the company. The sponsor company is developing a "Construction System" in order to improve the performance of its projects, and earlier research in this field has shown that Lean interventions, when applied to a case study project, have had positive results. This paper describes the next phase of the development of the Construction System, and proposes a Lean and agile production system model which is to be implemented on a major private finance initiative (PFI) hospital development, and in particular the mechanical and electrical (M&E) elements. The model builds upon a "leagile" concept developed from manufacturing theory, and shows how the need for Leanness and agility depends upon a total supply chain and labour strategy.

KEY WORDS

Construction System, performance improvement, Lean interventions, Lean and agile, mechanical and electrical, leagile, total supply chain, labour.

INTRODUCTION

This paper represents “work-in-progress” as part of a collaborative research project being undertaken at the Centre for Innovative Construction Engineering for an Engineering Doctorate at Loughborough University, UK. The programme is funded by the EPSRC and is sponsored by a major UK mechanical and electrical contractor (the company). The project will have specific objectives, which will be capable of making a significant contribution to the performance of the company.

The themes of the research project are “Innovative Construction Technologies” driven by the desire to use leading edge research and learning to improve the business of the sponsoring company. The sponsor company is a major provider of advanced mechanical, electrical and communications solutions in the construction sector in the UK. It works for customers in banking, retail, leisure and commercial property development, as well as education, health, defence and government offices, secure establishments and airports.

RESEARCH PROJECT OBJECTIVE

To be clear about the objective of this project, it is about improving site operations, making them safer for the worker, and improving efficiency and productivity. Since previous research was conducted (Court et al. 2005), an Incident and Injury Free programme has been introduced into the company. The safety leadership team state that the company is prepared to invest whatever is necessary to drive improvement in health and safety to ensure everybody returns home safely. "Failure to do so renders the company valueless." Also, the company is embarking on a programme of improving the performance of its projects by the introduction of a "project delivery standard." One component of this standard is to "adopt Lean and agile processes to compete with the worlds leading businesses." From this, it can be seen that the key elements to focus upon as further research project objectives are:

1. Everyone is to return home safely (from the construction site)
2. To adopt Lean and agile processes to compete[46] with the worlds leading businesses

Everyone returning home safely cannot just mean preventing incidents and injury in the traditional sense. It must also mean good ergonomics for the worker. Ergonomics, which in the industrial workplace is generally defined as a variation of the following:

"A science devoted to determining the range of anatomical, physiological and psychological human factors and designing work environments conducive to these ranges with the objective of maximising productivity and minimising injury" (McNamara, 1986). It is expected also, that by adopting Lean and agile processes a state of competiveness will occur. This is interpreted as putting the company ahead of its competitors in terms of profitability and position in the marketplace[47].

Manufacturing is seen as a rich source of research for Lean and agile concepts, so this was a primary source of research data for this project, as will be shown. This project therefore has the objective of designing and implementing a way of working on site that will satisfy these company objectives; to be Incident and Injury Free and to adopt Lean and agile processes to compete with the worlds leading businesses. Earlier research in this field has shown that

[46] To compete: To strive consciously or unconsciously for an objective (as position, profit, or a prize)**:** be in a state of rivalry (Merriam-Webster online dictionary)

[47] Source: The Company.

Lean interventions, when applied to a case study project, have had positive results (Court et al. 2005). These interventions were to form part of the design of a "Construction System", which is based on leading edge research and learning.

This paper describes the next phase of the development of the Construction System, and proposes a Lean and agile Construction System model which is to be implemented on a major private finance initiative (PFI) hospital development, and in particular the mechanical and electrical element and the associated interfacing trades. The model builds upon a "leagile" concept developed from manufacturing theory, and shows how the need for Leanness and agility depends upon a total supply chain and labour strategy.

UNDERPINNING THEORY

The next phase of the research project has focussed on research and learning from manufacturing, and in particular, Lean and agile theory. This enables a strong fit and even an interpretation of what adopting Lean and agile processes actually means, and then preparing to put this into practice in the real world. The research and learning undertaken has been used to develop a Construction System model that incorporates manufacturing techniques such as; leagility, modular assembly, reflective manufacture, ABC inventory system and pulse-driven scheduling. The boundaries of the production system model will be described, and its applicability to a large complex mechanical and electrical project. The expected benefits to the company as a result of this research project will also be described. In order to gain an understanding of the development of the model, the underpinning manufacturing theory will be described, together with further data collected necessary to aid the design and development of the Construction System. The Construction System itself will then be described.

LEAN AND AGILE MANUFACTURING – LEAGILITY

According to Mason-Jones et al. (2000) Lean and agile paradigms, though distinctly different, can be and have been combined within successfully designed and operated supply chains. Naylor et al., 1999, define leagility as:

"…the combination of the Lean and agile paradigm within a total supply chain strategy by positioning the decoupling point so as best to suit the need for responding to a volatile demand downstream yet providing level scheduling upstream from the decoupling point."

Techniques in Lean tend to suit the highly efficient producer, particularly the production of high variety commodity items at minimum cost. Lean is efficient but can it also be responsive? Lean seems to be much more appropriate for efficiency and cost cutting.

Agility stresses different values to Lean, typically learning, rapid configuration, and change. However, Lean and agile may be complimentary in the sense that you can join one system to another. For example a Lean factory could be joined to an agile supply chain. The coupling of "Lean" and "Agile" is often known as "Leagile." Following this logic a factory can be linked to its supply chain in three possible ways, and this is shown in table 1.

Table 1 Three ways to link a factory to its supply chain

Factory	Supply chain	Product type
Efficient (Lean)	Efficient (Lean)	Commodity items with predictable demands
Efficient (Lean)	Responsive (agile)	Mass-customised items
Responsive (agile)	Responsive (agile)	Fashion or innovative products with unpredictable demand

Agility is the ability to rapidly reconfigure the production system (and the supply and distribution systems) to meet new product requirements. Agility has a responsiveness dimension which does not seem to be part of the Lean definition.

It is possible to link different sorts of systems together using the concept of the decoupling point. For example the Lean factory can be separated from the agile distribution chain by means of a decoupling store. The factory will produce modules that are placed in the store and as the demand changes the modules can be quickly assembled in the distribution chain to provide the customer with a unique offering.

If the decoupler is moved very close to the customer so that it is far downstream then you have a “form postponement” strategy where the module store is close to the retailer and they have the means to rapidly assemble the product to meet the precise customer order. If the distribution of the product is delayed to the last minute and only configured and distributed when the customer order is received then you have “logistics postponement.”

Postponement implies major changes to the systems of production and distribution. The factory produces a range of modules that enable high variety products, and can be quickly assembled into final form. With form postponement the retailers are provided with simple fixtures with all tools that enable them to rapidly configure the product to meet the customer’s requirement. Such a strategy provides mass customisation. A form postponement decoupler is shown in figure 1.

Previous research has been conducted applying a leagile model to house building in the UK (Childerhouse et al. 2000). The report explains the application of leagility in the UK house building industry, which builds upon the research of Naim et al. 1999.

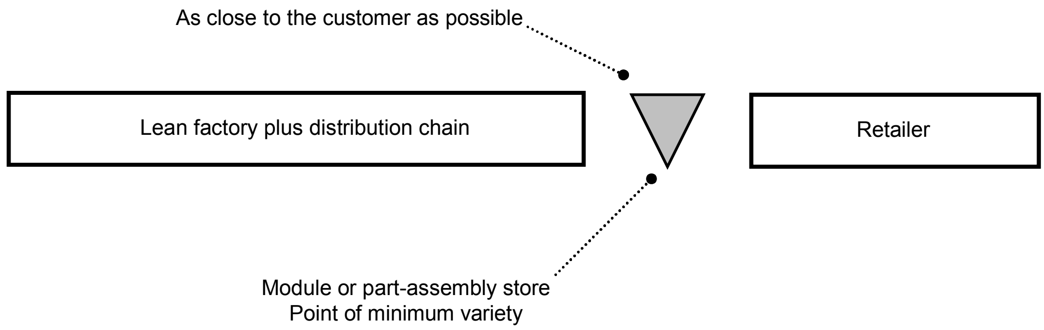

Figure 1 Product Stream

MODULAR ASSEMBLY

According to Fredriksson, 2006, modularity is a design strategy that is used by companies producing such different products as aircraft, household appliances, trucks and cars, computers and software. The popularity of the concept he describes, is explained by its appealing logic, which is to divide a complex system into decoupled and manageable modules that are easily put together into a working whole. A definition of this is given as:

"...the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks."

Modularity in production thus implies a dispersed assembly system, in which some activities are pre-assembly (of components into modules) and other activities are final assembly (of components and modules into end-products). This is shown in figure 2.

Much research covering modularity[48] in construction has been conducted, see Pasquire et al. 2002, and Pasquire et al. 2003 and Construction Industry Research Association (CIRIA), 1999, which has dealt with this concept, and according to Ballard and Matthews (2004), a Lean ideal for the championship, Prefabrication and Assembly, is to “simplify site installation to final assembly and commissioning”.

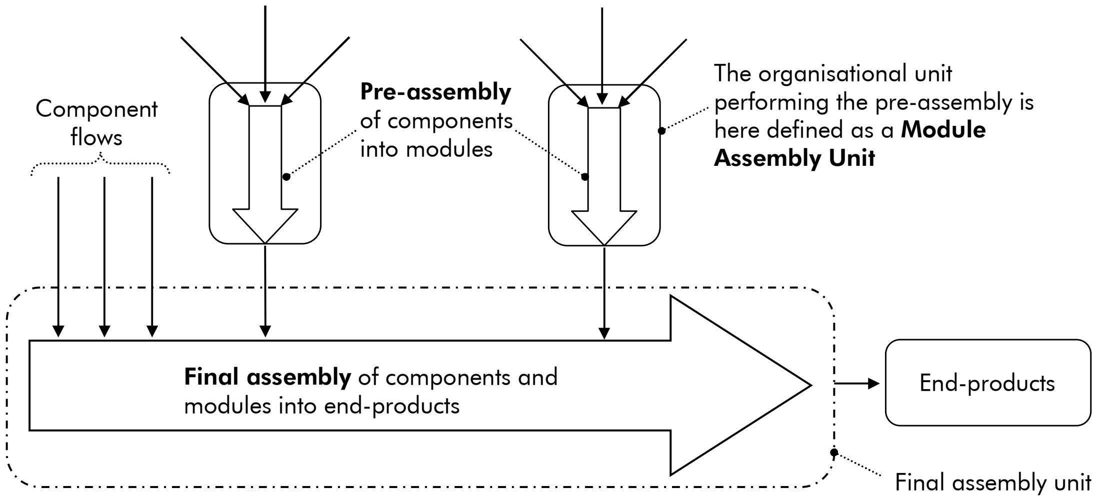

Figure 2 Modularity in production (Figure 1 in Fredriksson 2006)

This said the authors believe that a real contribution to this research is how modularisation can be incorporated into a wider Construction System, in the same way that manufacturing has used this strategy. This will be shown later. It is also expected that by implementing a strategy of modularity, health and safety risks on site will be reduced. HASPREST[49] is a tool which will be used to establish the extent of the effect of standardisation & pre-assembly on health, safety and accident causality in construction. Benefits will be obtained by being able

48 Modularity: Also referred to in this report as modular assembly, offsite manufacture, standardisation and pre-assembly, all of which are derived from referenced research reports. IGLC championship defines this as prefabrication and assembly.

49 The effect of Standardisation and Pre-assembly on Health, Safety and Accident Causality in Construction.

to include health and safety aspects in the consideration of modularity. A further benefit to applying modularity in construction is reducing the risk to projects due to skills shortages in the UK. Goodier et al (2006), in a research project looking into barriers and opportunities for offsite (manufacture) in the UK found that electricians, joiners and bricklayers were the three skills generally cited the most by all the sectors questioned as being in short supply and contributing to the increased demand for offsite products.

REFLECTIVE MANUFACTURE AND QUALITY OF WORK

Reflective manufacture is an important socio-technical approach to manufacture that arose in Sweden at the Volvo Uddevalla plant. Its evolution is described by Granath, 1998. It was regarded in Sweden as a person centred approach to automobile assembly although it was never fully developed. It is now attracting more attention with the development of mass customisation strategies. Reflective systems do vary in the way that they are designed; however, they tend to suit a highly modularised product. Also, research has found that Volvo, when looking into the development of production systems, looked into quality of work as well as efficiency of production. Quality of work, according to Granath, contains a number of aspects. He suggests that a system that offers professional meaningful work is better than those that only offer unskilled or semi-skilled work. The aspects that signify professional work are control over methods, time and quality plus the responsibility to plan ahead and the knowledge needed to reflect on work done. Quality of work also means good ergonomics, appropriate working tools and a good working environment.

A typical form of reflective system generally has module build units or cells each the responsibility of a semi-autonomous team. Team members are multi-skilled and highly trained so that they are interchangeable. There are likely to be standard operating procedures (SOP's) but members themselves generally design these. In these systems there is often a significant materials acquisition unit with a kitting function. The system operates using the "pulse" system or period batch control. Period batch control (also know as period flow control) is a Just-In-Time, flow control, single cycle, production control method, based on a series of short standard periods generally of one week or less.(Burbidge 1996). Alternatively, the System operates using an ABC inventory system (described later). Figure 3 shows a typical system.

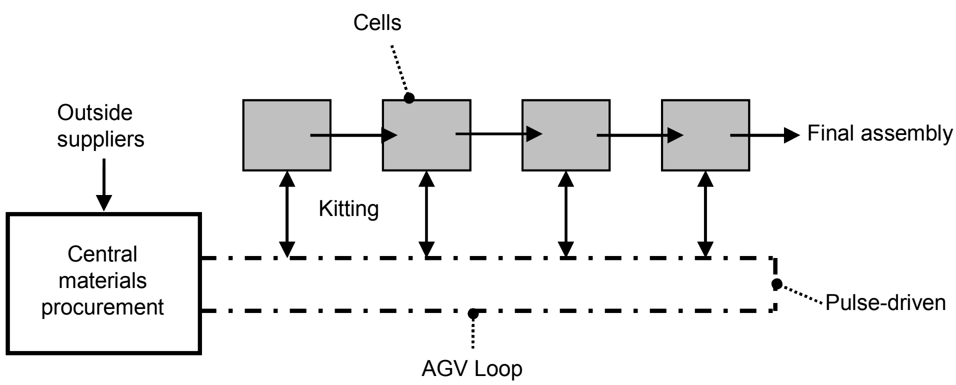

Figure 3 Reflective system

This approach suits a postponement strategy as shown in figure 4.

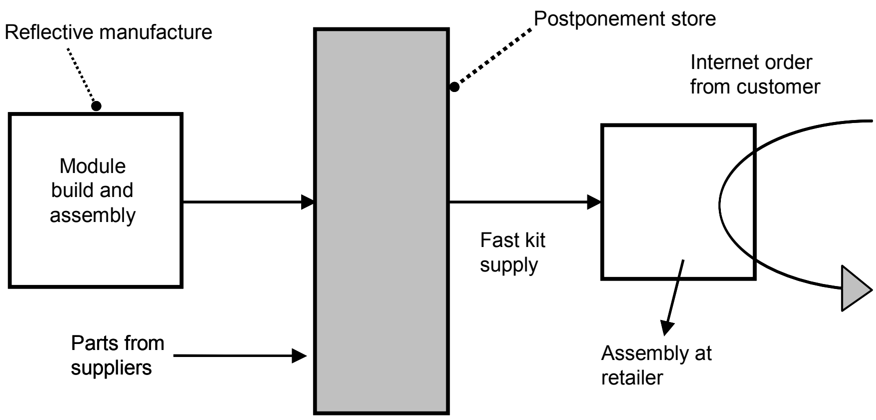

Figure 4 Postponement Approach

ABC INVENTORY SYSTEM

ABC analysis is based on Pareto analysis or the 80/20 rule. In inventory control 80% of the items need 20% of the attention, while the remaining 20% need 80% of the attention. They are categorised as follows: A items are expensive, critical and needing special care (modules). B items need just standard care (components). C items need little care (consumables such as nuts, bolts, washers etc). It is common to use different control strategies for the A, B and C parts. The control strategy depends upon the product complexity and the nature of demand, but typically: A parts are ordered using a "call-off" system. B parts are ordered conventionally using an MRP system. C parts are ordered using a simple inventory management system like the two bin kanban system.

FURTHER DATA COLLECTION

During the course of the design of the Construction System, further data was collected for the design of trade team specific mobile work cells. This was conducted in a focus group session with representatives from electrical workers, mechanical pipe workers, and duct workers. A focus group is a form of qualitative research in which a group of people are asked about their attitude towards a product, concept, advertisement, idea, or packaging. Questions are asked in an interactive group setting where participants are free to talk with other group members. In the world of marketing, focus groups are an important tool for acquiring feedback regarding new products, as well as various topics. In particular, focus groups allow companies wishing to develop, package, name, or test market a new product, to discuss, view, and/or test the new product before it is made available to the public. This can provide invaluable information about the potential market acceptance of the product.

The aim of the focus group session was to identify the complete kit required for each specific task to be completed at each stage of the site operation, with everything that is needed, factoring in: access and egress to and from the workplace, access equipment, tools, personal protective equipment, materials handling devices, and task lighting etc. It also included discussions on how material flows should be conducted on site, to the point of use. This data was collated and used to design trade team specific mobile work cells, and the work system itself. This builds upon the previous research (Court et al. 2005), implementing mobile work cells and ergonomic access equipment designed and used in a case study project.

In order to formulate an understanding of manufacturing concepts in the context of this research, an ethnographic study was undertaken. Ethnography is a style of research rather than a single method and uses a variety of techniques to collect data, (Cassell et al. 2004). This was an observational study conducted at the BMW "Mini" factory in Cowley, UK. This was to observe the assembly of the car body and the final car assembly process, to give the authors a "feel" for the manufacturing and assembly environment, and how people worked. It is not meant here to expand upon the Mini manufacturing process, but more importantly, the authors, by observing the various assembly processes conducted either by robots or people were able to get many visual clues as to how the techniques could be transferred to the Construction System model.

THE CONSTRUCTION SYSTEM

Previous research by the authors, Court et al. 2005, found that Lean interventions, when applied to a case study project, had positive results in terms of improving the performance of the project. These interventions were the first stage of designing and implementing a Construction System for the company. The findings from this research were to be used to inform and develop standardised operating procedures and routines for how work will be conducted in the future on new projects. This was to be together with new Lean features to be researched, developed, implemented and tested on these new projects, which would be reported on in the future. The development of the Construction System model represents this next phase of research, and is to be implemented on a case study project.

The Construction System model is represented in figure 5. Its underpinning theory has been described earlier in this report, and incorporates manufacturing concepts such as leagility, modular assembly, reflective manufacture, ABC inventory system and pulse-driven scheduling. To explain the model, the supply chain has been categorised in an ABC inventory system, with modules (category A) being delivered to site on a call-off system. Components and consumables (category B and C) will be parts kitted for delivery to site via a postponement store (this could be operated by the supply chain). Site operations are to be conducted by semi-autonomous teams (T1, T2 etc), using mobile work cells and ergonomic access equipment (Court et al. 2005) specifically designed for their activity. The System operates using the "pulse-driven" system, which has been called the "Week-Beat."

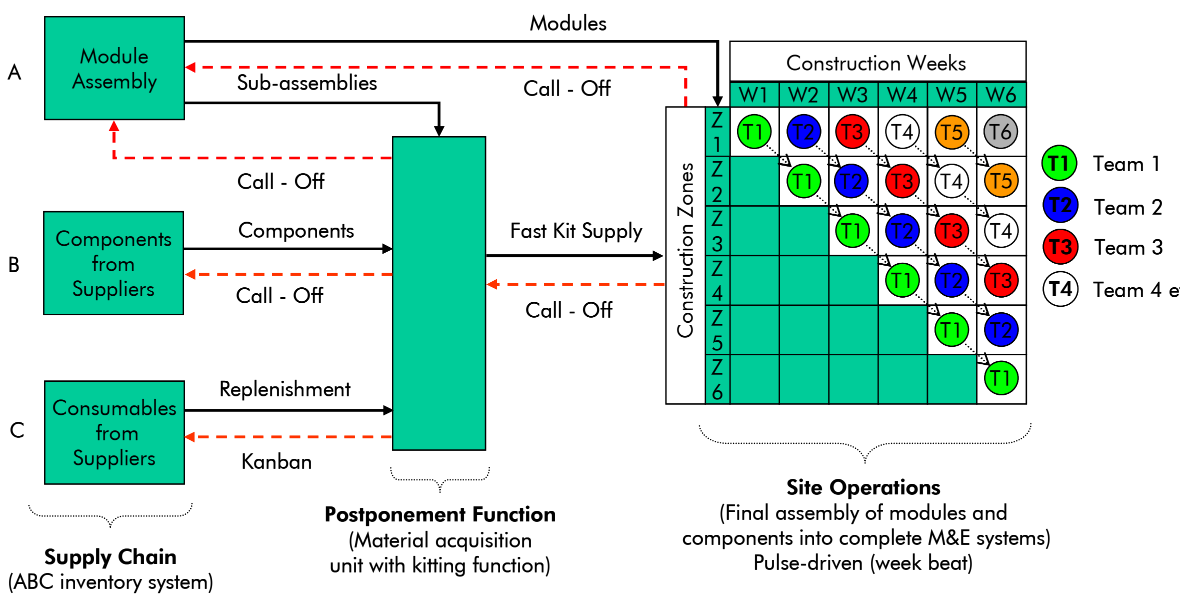

Figure 5 Construction System Model

TURNING THEORY INTO PRACTICE

Work has been done already to design and implement the various elements of the Construction System, and is now described.

Modular Assembly

The installations have been designed for modular assembly (off site manufacture), and will be in modular format, being either complete assemblies or sub-assemblies as appropriate. Examples of these are shown in figure 6, a corridor services module, and figure 7, an underground service tunnel module. The following elements are under consideration for modularisation: Corridor and riser modules incorporating building fabric, plantrooms and plantroom sub-assemblies (pump skids etc), bathrooms / integrated plumbing systems (IPS), clinical spaces (such as theatres etc), partition walls with services incorporated, modular wiring / busbars / wireless fire alarms, furniture and fittings with services incorporated.

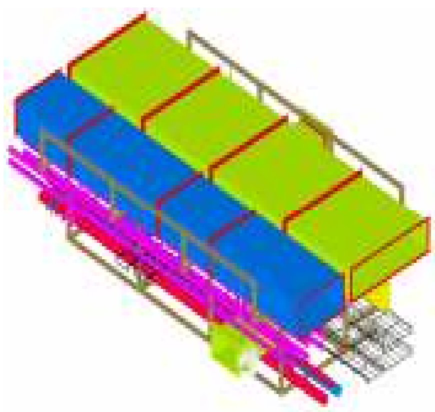

Figure 6 Corridor Module

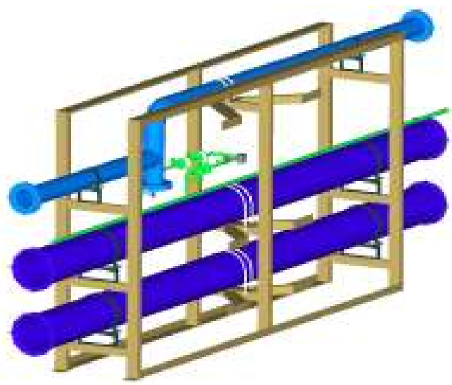

Figure 7 Underground service tunnel module

Postponement and Parts Kitting

In the System there is a significant materials acquisition unit with a kitting function, shown as part of the postponement store concept. As has been described, the System operates using an

ABC inventory system, where materials have been categorised accordingly and will flow directly to site, or via the postponement store for kitting prior to being sent to site on a Just-In-Time basis. Postponement here refers to the kits of materials being postponed until the moment they are needed, which are "called-off" by the site installation teams to suit their specific requirements, this being a derivative of "form" postponement described earlier.

A related form of the postponement concept has previously been implemented at the T5 project, Heathrow Airport, called the market place for demand fulfilment, and this is for civil works consumables, personal protective equipment, hand tools, power tools and consumables for power tools. This was the subject of the paper, "Kanban in Construction", Arbulu et al. 2003. The strategy was developed based on five key principles, these were:

1 Materials must be pulled through the supply network as needed at the workface.
2 Materials must arrive at the right place, at the right time, in the right quantity.
3 The supply network is achieved at the best value for the customer (not necessarily the best price).
4 All necessary actions are taken to minimise vehicle movements on site.
5 All necessary actions are taken to increase workflow reliability on site.

Of particular importance was the further conclusion from the analysis undertaken was the need to rationalise product profiles. This reduces the stock profile by replacing products with others that have similar functionalities; i.e. to standardise. It is expected that this research will shape the further detailed design of the postponement function and parts kitting method for the Construction System.

Mobile Work Cells and Ergonomic Access Equipment

Trade teams will be deployed on site with mobile work cells and ergonomic access equipment (Court et al 2005). This facilitates an environment for "quality of work (Granath, 1998). The work cells are being designed specifically for the trade teams, using data collected from the focus group research exercise discussed earlier.

The specific purpose of these interventions is to eliminate unnecessary motions for the tradesman getting to the place of work, and to have the necessary tools, components and consumables at hand to carry out the work uninterrupted.

Pulse-Driven

The System operates using the "pulse" system, which has been called the "Week-Beat." Here, each team has one week in each construction zone (approximately 1000 square meters) to complete its work before moving to the next zone and so on. The next team, T2, follows on at the Week-Beat interval, and the next, T3, team follows similarly. Requirements for the Week-Beat are: Each team has to work at the rate at which the previous team makes the working area available to them, so as to provide a continuous flow of work. The size of each team may be increased or decreased but the actual pace of physical effort is never changed. Each team has to carry out their designated amount of work in the planned time so as to make the working area available for the subsequent trade. Timing has to be such that each team can complete their work in the zone and move to the next zone without waiting for it to become available or starting early. The rate at which each item of work is carried out is to pull materials onto the site, to the work area, on a Just-In-Time basis, specifically for the task and without being stored on the site, in kit form, on mobile carriers or roll cages. Access equipment and tools are designed specifically for the area in which the work is to be carried out, and the rate at which the work is to progress. The rate at which each item of work is carried out is to pull drawings and information onto the site, being always the latest, most up to date and approved for construction. A similar method has been implemented on previous case study projects; see Court et al. 2005 and Horman et al. 2002.

Other System Features

Other Lean features of the Construction System which will be deployed are the Last Planner System of production control, and IMMPREST[50]. Last planner is a production planning and control tool used to improve work flow reliability. It adds a production control component to the traditional project management system. (Henrich et al. 2005). This method is being employed through the various stages of the project, starting with the design phase. IMMPREST is an interactive tool to measure the risks and benefits of using prefabrication within a construction project, Pasquire et al. 2005.

DISCUSSION

Reflective manufacture involves cells of autonomous teams producing modules to be incorporated into a final product. The System operates using the "pulse" system or period flow control. The System can also operate using an ABC inventory system. The final form of the product is postponed until the exact customer requirements are known.

Modular assembly is the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks. The Construction System will modularise main elements of the M&E systems; plantrooms, plantroom sub-assemblies,

[50] Interactive Model for Measuring Preassembly and Standardisation in construction.

risers, horizontal distribution, partition walls including service drops, bathrooms etc, all of which will be assembled off-site, and delivered Just-In-Time for incorporation into the final assembled system, by autonomous trade teams.

The Construction System has autonomous trade teams incorporating modules and component kits into the final assembled system. This is operated by a pulse-driven schedule, known as the "Week-Beat." Delivery of the component kits is postponed until the exact configuration is known and delivered to site Just-In-Time, to the team's specific requirements. The components are selected from a project catalogue from standardised items. Consumables will be replenished using a simple two-bin kanban system.

The model developed builds upon a "leagile" concept developed from manufacturing theory, and shows how the need for Leanness and agility depends upon a total supply chain and labour strategy. The supply chain strategy is clear; to modularise as much as possible off-site, to be delivered Just-In-Time, and incorporated into the final assembled systems along with component kits in a series of small and simple tasks. The labour strategy is also equally as clear; to remove as much labour off site as possible, those that remain must be provided with ergonomics, appropriate working tools and a good working environment, thereby facilitating a "quality of work."

Previous research by Childerhouse et al. 2000, and Naim et al. 1999, proposed a leagile model to be applied in construction, and in particular house building in the UK. The agile dimension providing flexibility of customer choice at various stages in the house building value chain, and is a robust and valid model. The customer here being the end user, or purchaser of the house. The model proposed in this paper provides an alternative proposition to leagility in construction. The customer requiring flexibility in the Construction System is the construction site itself, and in particular the autonomous trade teams.

The expected benefits of the System to the company are to improve health and safety on its projects, to ensure that everyone goes home safely, and to improve efficiency and productivity. If productivity is improved, there is a high probability that profitability will improve also. This is because there is a direct relationship to poor productivity and the final profitability of projects (Court et al. 2005). A further benefit will be offsetting the risk to the company of skills shortages in the UK construction industry. This is because there will be a reduced demand for labour on site due to off-site manufacturing being facilitated by the System. Finally, the company may have found a way to adopt Lean and agile processes, and because of this, in the opinion of the authors, will be positioned to compete with the worlds leading businesses, as the vision requires them to do so.

Although it is not the subject of this paper, an interesting matter for discussion is the influence the Construction System will have on project management. Whilst the Construction System has been received well by the company, in particular the projects sponsors, it is very much seen as research and development, and “let’s see how it goes.” It has also been well received by the immediate project team as it has been developed alongside them, stage by stage. Also, the authors have considerable influence on the case study project (one of the authors is the M&E Project Leader), and in this respect there is no alternative to its implementation. The System is very much an intervention into what would otherwise be normal project management practices. Its influence on project management may well be worthy of a research study on its own.

FURTHER RESEARCH

The next phase of research will be conducted by applying the Construction System to a case study project. The project selected is the mechanical and electrical (M&E) element of a large Private Finance Initiative (PFI) hospital, to be built in phases over a five year period, and an

M&E value in excess of £100 million. Further research will also be undertaken to design in more detail certain elements of the Construction System. These are: developing the ABC inventory system by standardising modules, components and consumables into a project catalogue; the postponement function with the fast kit supply methodology; developing the Week-Beat system and further designing "quality of work" for the worker. The results emerging from this and the Construction Systems implementation on the case study's initial phases will be reported on in future papers.

REFERENCES

Arbulu, R., Ballard, G., Harper, N. (2003). Kanban in construction. Proceedings of the 11th annual conference of the International Group for Lean Construction, Blacksburg, Virginia, July 22nd-24th, 2003.

Ballard, G. and Matthews, O., (2004). Championship – prefabrication and assembly. Proceedings of the 12th annual conference of the International Group for Lean Construction, Elsinore, Denmark, August 3-5, 2004.

Burbidge, J.L., (1996). Period flow control. Clarendon Press, ISBN 0198564007.

Cassell, C. and Symon, G., (2004). Essential guide to qualitative methods in organisational research. SAGE publications.

Childerhouse, P., Hong-Minh, S.M., and Naim, M.M., (2000). House building supply chain strategies: selecting the right strategy to meet customer requirements. Proceedings of the 9th annual conference of the International Group for Lean Construction, Brighton, UK.

Construction Industry Research and Information Association, (1999). Standardisation and Pre-Assembly: adding value to construction projects. CIRIA report 176, ISBN 0-86017-498-0.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia.

Fredriksson, P., (2006). Mechanisms and rationales for the coordination of a modular assembly system – The case of Volvo cars. International Journal of Operations and production Management, Vol 26 No. 4 pp 350-370.

Goodier, C.I., Gibb, A.G.F., (2005). Barriers and opportunities for offsite in the UK. Systematic innovation in the management of projects and processes. Abdul Samad Kazi (ed), cib Helsinki international joint symposium, pp. 148-158, ISBN 952 5004 64 3.

Granath, J.A., (1998). Torlanda to Uddevalla via Kalmar: A journey in production practice in Volvo. Seminário Internacional Reestruturaçã Productiva, Flexibilidade do Trabalho e Novas Competências Profissionais COPPE/UFRJ, Rio de Janeiro, Brasil.

Henrich, G., Tilley, P., Koskela, L., (2005). Context of production control in construction. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia.

Horman, M.J., Messner, J.I., Riley, D.R., Pulaski, M.H., (2003). Using buffers to manage production: a case study of the pentagon renovation project. Proceedings of the 11th annual conference of the International Group for Lean Construction, Blacksburg, Virginia, July 22-24, 2003.

Mason-Jones, R., Naylor, B., and Towell, D., (2000). Engineering the leagile supply chain. International Journal of Agile Management Systems, 2/1, 54-61.

McNamara, Brian E (1986). Ergonomics: maximising the human resource. Logistex Forum, May 6-8, 1986.

Naim, M.M., Naylor, B., and Barlow, J., (1999). Developing Lean and agile supply chains in the UK house building industry. Proceedings of the 8th annual conference of the International Group for Lean Construction, California, USA.

Naylor, J. B., Naim, M. M., and Berry, D., (1999). Leagility: integrating the Lean and agile manufacturing paradigms in the total supply chain. International Journal of Production Economics (1999), No. 62, pp. 107-18.

Pasquire, C.L., and Connolly, G.E., (2002). Leaner construction through off-site manufacturing. Proceedings of the 10th annual conference of the International Group for Lean Construction, Gramado, Brazil.

Pasquire, C.L., and Connolly, G.E., (2003). Design for manufacture and assembly. Proceedings of the 11th annual conference of the International Group for Lean Construction, Blacksburg, Virginia, July 22-24, 2003.

Pasquire, C.L., Gibb, A.G.F., and Blissmass, N., (2005). What should you really measure if you want to compare prefabrication with traditional construction? Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia.

APPENDIX C PAPER 3 (JOURNAL, PUBLISHED)

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2009). Modular assembly with postponement to improve health, safety and productivity in construction. J. Practice Periodical on Structural Design and Construction, 14(2), 81-89.

MODULAR ASSEMBLY WITH POSTPONEMENT TO IMPROVE HEALTH, SAFETY AND PRODUCTIVITY IN CONSTRUCTION

Peter F. Court, Christine L. Pasquire, Alistair G.F. Gibb, David Bower

ABSTRACT

This paper presents the outcome of an engineering study as part of the design and development of a Lean and agile Construction System and in particular its supply chain component. This combines modular assembly with a postponement function to be tested on a case study project (not reported here), the objective of which is to improve health, safety and productivity for the company sponsoring the research.

The contribution to research is the combination of countermeasures described in this paper that have been developed and incorporated into a wider Construction System, in the same way that manufacturing has used this strategy with great success. Also, a further output is the development and use of an innovative method for assembling, transporting and installing mechanical and electrical modules, whereby modularization can be achieved with or without offsite manufacturing capability. The research forecasts a reduction of onsite labor of 35% compared to using traditional methods of construction, with less onsite operatives at risk of injury carrying out simpler assembly tasks within ergonomic mobile work cells. Further research is proposed to measure the benefits of the Construction System following its implementation on a case study project.

CE Database subject headings: Construction industry; Lean Construction; Labor; Safety; Productivity; Prefabrication.

INTRODUCTION

This is a practical paper drawn from a collaborative research project (the research project) being undertaken at the Centre for Innovative Collaborative Engineering at Loughborough University, UK. The programme is funded by the Engineering and Physical Sciences Research Council (EPSRC) and is sponsored by a major UK mechanical and electrical (M&E) contractor. The research project has specific objectives which will be capable of making a significant contribution to the performance of the sponsor company (the company).

The company is developing a Construction System in order to improve the performance of its projects, and earlier research in this field (Court et al. 2005) has shown that Lean interventions when applied to a case study project had positive results. The next phase of the research (Court et al. 2006, 2007) using leading edge research and learning, designed a Lean and agile Construction System which is to be implemented on a major private finance initiative (PFI) hospital development, and in particular the mechanical and electrical elements within it (the case study project). This paper reports the next phase of the research project, which is the design of the supply chain component of the Construction System, combining modular assembly with a postponement function. The paper will start by setting out the research project objectives, followed by background review of the UK construction industries health, safety and productivity performance. The underpinning theory and further related research findings are then presented which together form the basis of the design of the Construction System. Following this the Construction System itself is described, along with the case study project. The process to achieve the design of the modular assembly and postponement function is then set out, prior to the component itself being described. Finally, the expected benefits of the System are described (with certain results), conclusions are then drawn from this phase of the research and the next phase of research is proposed.

PROJECT OBJECTIVES

The objective of this project for the company is to improve site operations, making them safer for the worker and to improve productivity as a countermeasure to the prevailing conditions in UK construction and the company itself. Safety is at the core of the company and according to the Business Leaders *"...it is an absolute right for people to return home safely at the end of a productive day's work,"* and *"failure to do so renders the company valueless."* The key words here being *safely* and *productive,* these are therefore the key objectives of this research project, which is to design and implement a way of working on site, the countermeasures, that will satisfy these objectives.

INDUSTRY BACKGROUND

According to the Health and Safety Executive (HSE) 2007, 2.2 million people work in Britain's construction industry making it the countries biggest industry. It is also one of the most dangerous. In the last 25 years over 2,800 people have died from injuries they received as a result of construction work. Many more have been injured or made ill. The HSE (2007a) have identified that construction also has the highest rate of musculoskeletal disorders (MSD's). These are mostly back injuries from manual handling. There were 56,000 work related MSD cases in construction in 2004/5. Handling injuries (to employees in 2004/5) accounted for 38% of over 3 day injuries and 15% of major injuries. In their research into MSD's, the HSE (2007b) have identified areas that can create a risk, which include; repetitive and heavy lifting; bending and twisting; repeating an action too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment (e.g. hot, cold); psychosocial factors (e.g. high job demands, time pressures and lack of control); not receiving and acting upon reports of symptoms quickly enough.

UK M&E construction site productivity is poor. An investigative study by The Building Services Research and Information Association (BSRIA) set a foundation for understanding the problems and issues that the UK M&E industry faces within the construction sector (Hawkins 1997). BSRIA compared UK, American, German and Swedish construction projects to highlight productivity problems relating to M&E building services to assist the UK M&E industry in promoting improvements in productivity and to suggest remedies to solve these problems and improve performance. Significantly, the UK projects monitored had an average overall productivity of only 37% when compared to observed best practice and an average task productivity of only 56% by comparison. It found poorly conceived site parts storage and handling strategies which caused delays, with the very poorly performing projects being characterized by very poor levels of housekeeping. Workers were engaged in too much site cutting, drilling and assembly work and elevation of parts into final position. BSRIA report that labor costs typically constitute 30% of overall project M&E costs, so maximizing the output on site is essential in order to increase a contractor’s performance and the value for money investment of the customer.

The report, Innovative M&E Installation (Wilson 2000), follows on from Hawkins (1997) and recommended that alternative systems, components, materials and innovative methods should be thoroughly evaluated to identify opportunities for productivity gains on M&E projects. It concludes that the UK construction industry must replace outdated components and processes if it is to remain competitive in a global marketplace. This research found that the UK construction industry can realize a significant gain in installation performance through the adoption of innovative components and systems. Subsequent research conducted by BSRIA

(Hawkins 2002) concluded that UK construction project teams that implemented improvement strategies and actions in accordance with the BSRIA best practice recommendations have realized significant improvements in site productivity. The research found that teams that designed for high site productivity used innovative components and exploited offsite manufacture realized a step-change improvement in construction site productivity rates. It also found that whilst the use of innovative products and offsite manufacturing techniques can deliver a huge improvement in project performance, their true value was still not being fully exploited. Court et al. (2005) describes how the increased cost of labor on recently completed major projects had a severe negative impact on the financial outcome of those projects and because of the scale of the cost overruns, the company itself.

UNDERPINNING THEORY

Manufacturing is seen as a rich source of research data for the adoption of Lean and agile concepts into construction, therefore this was a primary source of theory for this research project. The research and learning has been used to develop a Construction System that incorporates manufacturing concepts such as; modular assembly, postponement, reflective manufacture (including pulse-driven scheduling – period flow control), and ABC parts classification. This was reviewed and described by Court et al. (2006).

Modularity is a design strategy that is used by companies producing such different products as aircraft, household appliances, trucks and cars, computers and software. The concept is to divide a complex system into decoupled and manageable modules that are easily put together into a working whole (Fredriksson 2006). A definition is given by Fredriksson as the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks. Postponement is an approach that helps deliver more responsive supply chains. Form postponement involves the delay of final manufacturing until a customer order is received and is commonly regarded as an approach to mass customization (Skipworth and Harrison 2004). Mass customization, is providing numerous customer chosen variations on every order with little lead time and cost penalty. The research proposes the application of form postponement as a solution to deal with the high demand uncertainty resulting from the provision of many variants, whilst ensuring low operational costs are maintained and short reliable lead times. If distribution of the product is delayed to the last minute and only configured and distributed when the customer order is received then you have logistics postponement (Yang and Burns 2003). Examples of how product architecture enables postponement are given in Ulrich and Eppinger (2004). They link the product architectural choices to platform planning, this being the collection of assets including component designs, shared by products. In Court et al. (2006) the customer requiring flexibility in the Construction System is the construction site itself and in particular the semi-autonomous trade teams requiring exactly what they need when they need it. In Liker (2004) each person or step in a production line or business process was to be treated as a customer and to be supplied with exactly what was needed at the exact time needed. According to Liker, this was the origin of Deming's principle; the next process is the customer. Reflective manufacture evolves from Volvo's development of production systems which looked into quality of work as well as efficiency of production. Quality of work contains a number of aspects (Granath 1998). Granath suggests that a system that offers professional meaningful work is better than those that only offer unskilled or semi-skilled work. The aspects that signify professional work are; control over methods, time and quality plus the responsibility to plan ahead and the knowledge needed to reflect on work done. Quality of work also means good ergonomics, appropriate working tools and a good working environment. The System operates using a pulse or period batch control. Period batch control (also know as period flow control) is a ‘Just-In-Time’, flow control, single cycle production control method, based on a series of short standard periods generally of one week or less (Burbidge 1996). Alternatively, the System operates using ABC parts classification. In most manufacturing systems, a small fraction of the purchased parts represent a large fraction of purchasing expenditures so management should therefore focus most attention on these parts. ABC classification is used to accomplish this (Hopp and Spearman 2001). Parts have been classified by Hopp and Spearman into A Parts - the first 5 to 10 percent of the parts accounting for 75 to 80 percent of expenditure; B Parts - the next 10 to 15 percent of the parts accounting for 10 to 15 percent of expenditure; and C Parts - the bottom 80 percent or so of the parts accounting for only 10 percent or so of expenditure. It makes sense therefore to use appropriate methods to tightly coordinate the arrival of A parts. The cost of holding small excess quantities of C parts is not large; therefore such methods would not be required for these. B parts are in between, so they deserve more attention than C parts, but less than A parts. The main point being that inventories of different classes of parts should be treated differently.

FURTHER RESEARCH FINDINGS

Related research findings to support this phase of the research are critical space analysis (Winch and North 2006), symbiotic crew relationships (Thomas et al. 2004) and sequence planning for electrical construction (Horman et al. 2006). According to Winch and North it is known that congestion on site reduces output and generates hazards. Thomas et al. report that symbiotic crew relationships occur when the pace of a crew depends on the pace of a preceding crew. Sometimes these relationships it was found are loose and relatively independent. At other times the relationships are tight and closely dependant. The research found that it is more common to have tight relationships in mechanical, electrical, plumbing and finishing trades. It defines this tight and dependant relationship as symbiotic. It found that the performance of crews with symbiotic relationships is shown to be consistently worse than when symbiotic relationships are not present. A method to avoid symbiotic relationships is recommended by simplifying the operations using preassemblies. This reduces the amount of work on site by fabricating and assembling M&E modules offsite and simply installing these with a small installation team**.** Horman et al. report on factors that bear significantly on the performance of electrical contractors in building construction projects. It found that when project work sequences are poorly planned or poorly executed, electrical constructors often must contend with compressed schedules, trade stacking and out of sequence work.

Considering health and safety factors, occupational health has been ignored in favor of the more immediate, high impact occupational safety (Gibb 2006). Gibb argues that occupational health incidents are to be considered as "slow accidents" – the period over which the incident occurs may be lengthy and may creep up on you unawares. This implies that the result will be the same as an occupational accident; in that a worker gets injured but it just takes longer. Gibb's keynote paper reports that in the UK 4,500 construction workers are absent from work every day because of injuries caused by accidents, but there are 11,000 construction workers off sick at any one time with a work-related illness.

Research conducted for its better backs campaign (HSE 2000) found that a change to prefabricated modules for mechanical and electrical works and the use of mechanical aids to lift them significantly reduced the risk of manual handling injury. This enabled employees to maintain an improved posture when connecting and testing the units. Other benefits were found in the study including a considerable saving in time, no storage space required, no full floor scaffold required and improved consistency and quality of work.

In a research project looking into barriers and opportunities for offsite manufacture in the UK (Goodier and Gibb 2005), it is reported that the UK construction industry has a historically low level of training when compared with other industries and it is estimated that between 70 and 80% of the workforce in construction in the UK has no formal qualifications. Also a large proportion of the workforce are laborers, many of them self-employed, their skill base is narrow and their training is limited. It found also that there is an estimated annual turnover of between 65,000 and 75,000 people per annum in the industry. Significantly, the research found that electricians, joiners and bricklayers were the three skills generally cited the most by all the sectors questioned as being in short supply and contributing to the increased demand for offsite products.

Taken together these collective research findings form the underpinning theory for this research project and present a compelling case to do something to improve business as usual practice, which must be of benefit to the company and to the construction industry as a whole. The Construction System is specifically designed to address these issues with appropriate countermeasures.

THE CONSTRUCTION SYSTEM

The Construction System is the proposed methodology to deliver the objectives of the sponsor company and is represented in figure 1. Its underpinning theory incorporates manufacturing concepts such as modular assembly, postponement, reflective manufacture and ABC parts classification (Court et al. 2006). Its key components are its supply chain with a postponement function and its Lean site operations. The supply chain component has been categorized using ABC parts classification with modules (type A) being delivered directly to site on a call-off system. Components and consumables (type B and C) being parts kitted or replenished for delivery to site via the postponement function also on a call-off system and to the exact requirements for the site operations. The kits are to be postponed until the moment they are needed. Figure 2 shows a digital prototype of a corridor module (type A parts) together with distribution systems emanating from it and those around it (type B parts). Site operations are conducted by trade teams (T1, T2 etc) using mobile work cells and ergonomic access equipment (Court et al. 2005). The System operates using a pulse-driven system which has been called the Week-Beat. The site operations component of the Construction System is the subject of separate research studies prior to its implementation on the case study project.

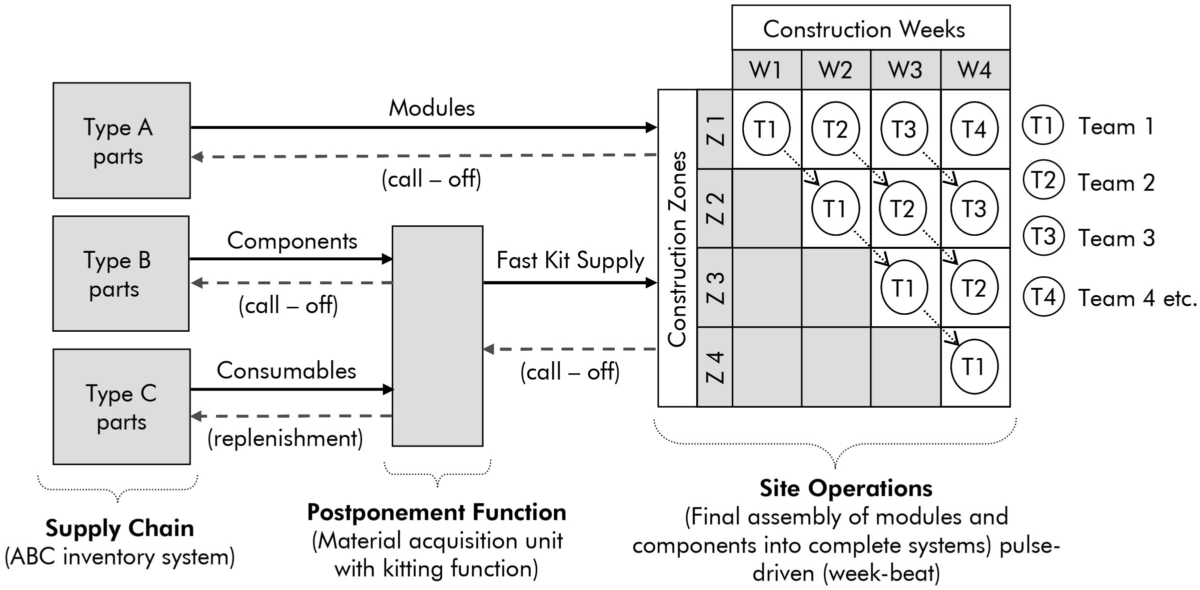

Fig. 1 The Construction System (developed from Court et al. 2006, 2007, 2008)

APPLICATION OF THE CONSTRUCTION SYSTEM

THE CASE STUDY PROJECT

The case study project is part of the development of a major acute hospital being procured using the UK Government's Private Finance Initiative (PFI). The project is to be developed in phases across two existing operational hospitals. The phases are a new Maternity and Oncology Centre (20,000 m² gross internal floor area); Sterile Services Department (2,000 m² gross internal floor area), Hub and Wards Unit (52,000 m² gross internal floor area); Diagnostic Treatment Centre (20,000 m² gross internal floor area); Community Hospital –

remote location (12,000 m^2 gross internal floor area). The project commenced construction in December 2006 (M&E commenced August 2007) and is due for completion in 2012.

The Construction System is being applied on each phase of the case study project the first being the new Maternity and Oncology Centre. This is a 20,000 m^2 building over four floors. It has electrical and water storage plantrooms in its basement with main ventilation plantrooms over the Oncology Centre at level two and on the roof at level five. Riser shafts are located around the building and distribute air, water, medical gas, electricity and the like throughout the building to the various departments. Corridor ceiling voids distribute the services from the riser shafts and then further into individual rooms and spaces, again in the ceiling voids. Finally, services distribute inside dry-lined walls to points of use such as electrical sockets, sinks, basins and bed-head units; everything you would expect to see in a new and modern healthcare facility.

Earlier work for this research project has described how the parts to be used that form the complete M&E systems on the case study project were categorized using ABC parts classification, with type A being modules, type B being loose components and type C being consumables such as nuts, bolts, washers and the like. Described in this paper is the research involved in setting the supply chain strategy. This is to pre-assemble as much as possible offsite (type A parts) to be delivered Just-In-Time and incorporated into the final assembled systems along with component kits (type B and C parts) in a series of small and simple tasks. The labor strategy is also clear; to remove as much labor offsite as possible with those that remain provided with good ergonomics, appropriate working tools and a good working environment, thereby facilitating a quality of work.

THE PROCESS: SET BASED THINKING

The M&E elements for ABC classification were agreed upon according to principles and ground rules pre-agreed by cross-functional teams. Liker (2004) called this set based concurrent engineering. This term was used to describe how Toyota developed vehicle designs using a cross-functional team of experts and the Project Leaders relied on that team. This was the starting point for actually deciding upon what chunks of the M&E systems were to be modularized (type A parts), and what would be parts kitted or replenished (type B and C parts), as well as the selection of the actual components themselves. This activity was conducted in a workshop environment, with project team members assigned to the team because of their individual expertise. The team members were represented with the following disciplines: Project Leader (one of the authors); Offsite Manufacturing Engineer; Construction Manager; Commissioning Manager; Maintenance Engineer; Mechanical and Electrical Engineer; Mechanical Design and Electrical Design Engineer; Architectural Technician; Structural Engineer; Procurement Engineer and component suppliers. The initial activity was to agree upon the guiding principles, design parameters and ground rules so that decisions were made in the light of these and the team would not move forward unless each had been satisfied. Three overarching principles were set and these are:

PRINCIPLE 1 INCIDENT AND INJURY FREE: People returning home safely every day after a productive days work; minimize on-site labor; health, safety and quality shall be the over-riding objectives of the design.

PRINCIPLE 2 DESIGN TO MAKE THE SITE ONE OF ASSEMBLY RATHER THAN CONSTRUCTION: Engage in systematic analysis of the elements and their interconnection; design for modular assembly; design for standardization; design solutions for re-use; engage the internal and external supply chain to deploy expertise early in the design process – design around a product.

PRINCIPLE 3 USE TECHNOLOGY ENABLERS: 3D/4D modelling (digital prototyping) is to be deployed throughout the project; fully integrated and co-ordinated, 3D common data structure; 3D intelligent objects provided by the internal & external supply chain (not the subject of this paper).

The outputs of these workshops are described later in this paper. Together with the workshops for parts analysis, construction sequencing was also agreed with a cross-functional team. The team consisted of nominated members from the parts classification team, as well as M&E, building, planning and specialist sub-contract trade personnel.

INSTALLATION SEQUENCING FOR CONSTRUCTION

A detailed analysis was undertaken of the installation sequencing, with particular emphasis on ensuring that no two or more trades would work in the same place at the same time, unless expressly designed to do so. The building is divided into construction zones; each being approximately 1,000 m^2 (zones 1-17, plantrooms 1-3). This area of construction zone being right-sized for each trade team to complete the planned work in a maximum five days. Here, team T1 has one week to complete its work before moving to the next zone. The next team, T2, follows on at the Week-Beat interval, and the next, T3, team follows similarly. Within each construction zone mechanical and electrical work has various sub-process activities, as do the building fabric works (dry-lining, ceilings, painting, flooring etc.). These tight and dependant relationship are what Thomas et al. (2004) called symbiotic and these relationships exist within this project. Table 1 shows the agreed sequences between each M&E process (MEP1, 2, 3 etc.) and associated building fabric processes (BFP1, 2, 3 etc.).

Table. 1 Construction zone process and associated activity schedule (developed from Court et al. 2007)

Process	Installation Activity
BFP1	Set datum's; mark out and fit dry lining header track.
MEP1	Drainage; ductwork; riser/corridor modules; distribution systems; insulation.
BFP2	Thin-bed screed; dry-lining studwork; first side dry-lining.
MEP2	Pipework and electrical conduit drops within dry-lining walls.
BFP3	Second side dry-lining; tape and joint; mist coat painting.
MEP3	Power and control cabling; medical gas pipe work; wall mounted equipment.
BFP4	Ceiling bulkheads; ceiling grid; service tiles for M&E devices; door frames.
MEP4	Ceiling mounted equipment.
BFP5	Vinyl floor; final painting; door sets and ironmongery; cupboards; fixed furniture.
MEP5	Connections to equipment; floor mounted toilets; door mounted accessories.
BFP6	Ceiling tiles (excluding commissioning access tiles); carpets; final clean.

Figure 2 represents a template construction zone process, mapped onto an assembly process as figure 1 in Fredriksen (2006).

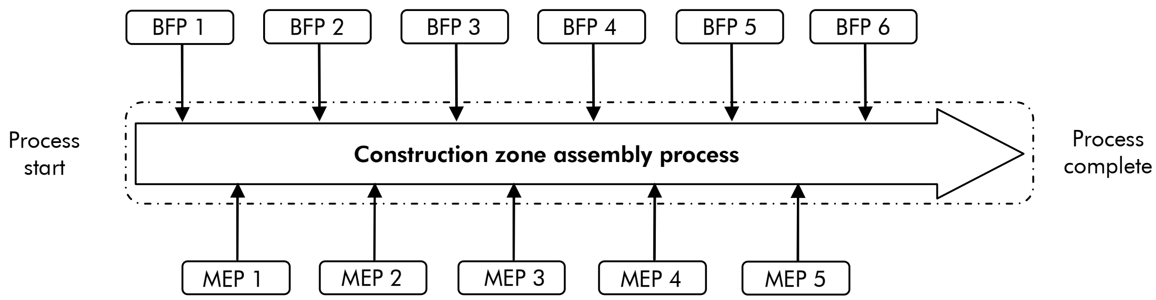

Fig. 2 Construction zone assembly process (developed from Court et al. 2007)

This shows the M&E processes (MEP1-5), and the building fabric processes (BFP1-6). The process starts with a designated construction zone is made available for work and finishes when all operations are complete.

As can be seen in table 1, each M&E and building fabric sequence has various sub-processes within it and MEP1 has been shown in figure 3. MEP1 consists of at least five sub-processes each of these conducted by separate teams.

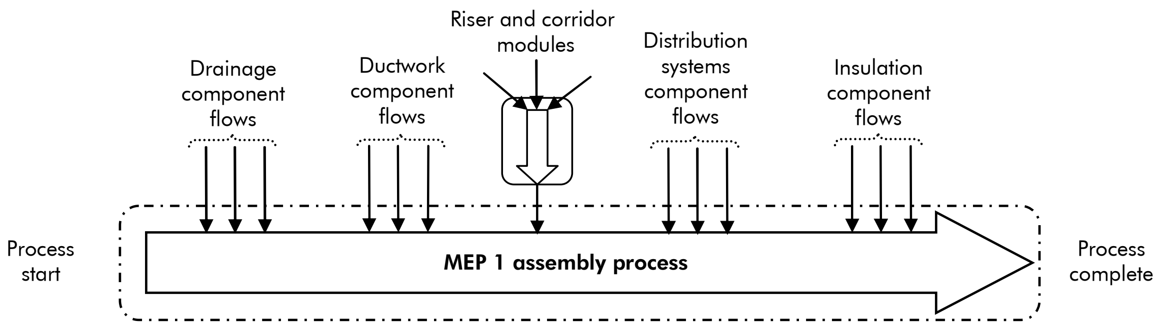

Fig. 3 Mechanical and electrical process 1 (developed from Court et al. 2007, 2008)

This figure now shows the outputs of the ABC classification team, where riser and corridor modules have been incorporated with the remaining MEP sub-processes being component supplied to be parts-kitted and postponed as described in this paper. MEP2-5 follow a similar format, with sub-process components and modules being assembled together to form the final M&E systems. These and subsequent assembly processes repeat in each construction zone with the aim of each sub-process being completed in the Week-Beat cycle. These processes rely on modules and parts being available in the right sequence and at the right time for the System to operate as planned. The approach to this is now described.

APPROACH TO MODULAR ASSEMBLY AND POSTPONEMENT FOR CONSTRUCTION ZONES

In order to design the component flows into the case study project, the cross-functional teams developed a logistics strategy to guide the teams thinking through the process, which is set as follows: There will not be a big central store of parts waiting to be used or workers having to walk to and from stores to collect parts. However, there will be parts on site today, being what is needed tomorrow with inventory check-lists used to guarantee complete kits are provided; Modules (type A parts) delivered direct to the point of use and incorporated using mechanical lifting gear by manual handling operatives; a logistics team delivering kits of type B parts for the next days work on carriers which are moved straight the point of use and replenishing type C parts into mobile work centers according to use. This logistics strategy set the thinking for how materials are to flow into the site. Because ABC parts are procured according to their type their supply chain source needed to be understood. To assist this, parts were further categorized into made-to stock and made-to-order type. A Lean ideal for the championship, prefabrication and assembly, is to simplify site installation to final assembly and commissioning (Ballard and Matthews 2004). In this ideal products used in the building process have been divided into made-to-stock (MTS) and made-to-order (MTO). An example of this further categorization is presented in table 2 for MEP1 and plantroom assembly processes. Other MEP processes (MEP2-5) follow a similar format.

Table 2 Example of ABC parts by MTS and MTO for MEP1 and plantrooms

Process	Type A Parts MTO	Type B Parts MTO	Type B Parts MTS	Type C Parts MTS
MEP1	Riser modules; corridor modules.	Ductwork and fittings; composite brackets.	Pipework and fittings; electrical tray and fittings; fire stopping sleeves; insulation.	Nuts; bolts; washers; screws; clips etc.
Plantrooms	Plant items; plant modules; distribution modules; electrical panels etc.	Ductwork and fittings; composite brackets.	Pipework and fittings, electrical tray and fittings; cables; insulation.	Nuts; bolts; washers; screws; clips etc.

When designing this System, of concern to the teams was the potential fragility of the System. A production system which culminates with Just-In-Time (JIT) is very efficient if everything runs perfectly, but is extremely fragile if there is any kind of problem whatsoever (Forza

1996). Further, in order to be able to function in a Lean system, all the resources being used in the production process have to be foreseeable and reliable. The Construction System has the potential to be fragile in this way as it is not embedded in company operations and tried and tested. Therefore component flows into the project have to be foreseeable and reliable in order for the Construction System to work as planned. Safety stock and safety lead times can be used as protection against these problems (Hopp and Spearman 2001). Safety stock should be used to protect against uncertainties in production and demand quantities, while safety lead time should be used to protect against uncertainties in production and demand timing. These countermeasures have therefore been built into the Construction System. Resource capacity buffers are built into site operations which is the subject of

CONSTRUCTION ZONE AND PLANTROOM MODULES (TYPE A PARTS - MTO)

An important point to note is that the company has its own manufacturing centre which has been producing modular M&E assemblies since the mid 1990's, and has previously been the subject of research studies (Pasquire and Connolly 2002, Pasquire and Connolly 2003). The authors believe that the contribution to research is how modularization can be incorporated into a wider Construction System in the same way that manufacturing has used this strategy. Also, by using an innovative method for assembling, transporting and installing corridor and riser modules (MEP1 sub-processes), as described later in this paper, elements of modularization can be achieved with or without manufacturing capability.

In figure 4 the initial corridor module design shows a rigid welded unistrut steel frame which contains the M&E components within it. However, once the module has been installed, most of the steel frame is redundant, therefore not adding value to the module other than during assembly and transportation from the place of manufacture (manufacturing centre). This adds additional cost to the module, which has been seen as a barrier to offsite manufacture (Goodier and Gibb 2005).

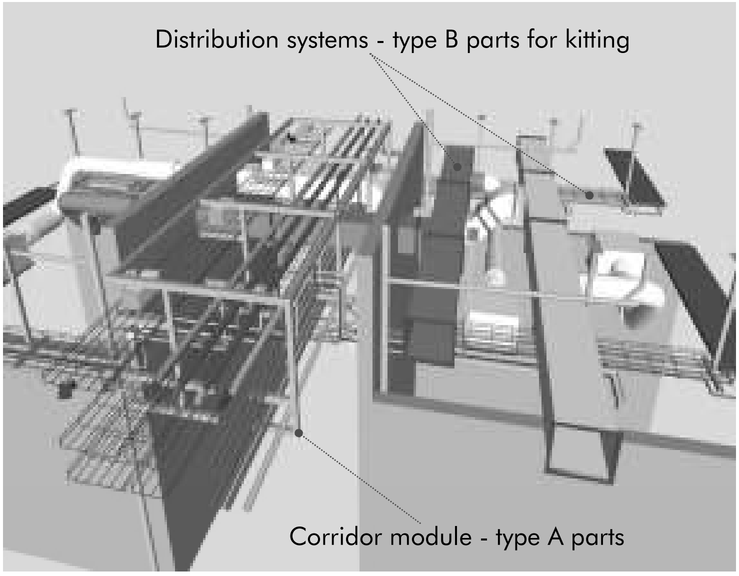

Fig. 4 Digital prototype of corridor module and distribution systems representing initial thinking

To overcome this, an assembly, transportation and installation frame (ATIF) was conceived. Here modules are assembled in the manufacturing centre, transported to site, incorporated into the building using mechanical hoists with the ATIF returning to the manufacturing centre for re-use. Figure 5 shows digital prototypes of three stages of this sub-process. The modules when lifted on the ATIF are bolted to cast-in unistrut inserts running in tram-lines along corridor positions in the concrete soffit. This avoids the need for workers drilling for fixings into concrete, reducing the risk of injury from hand-arm vibration.

Fig. 5 ATIF ready in manufacturing centre; elevation onsite using mechanical lifting hoists; modules installed with ATIF to be returned to manufacturing centre for re-use (developed from Court et al. 2008)

The modules and ATIF's have been standardized during the design process, in that there are two corridor widths and two corridor ceiling void heights giving four size combinations. The ATIF is designed to accommodate each of these four sizes by being reconfigurable via removable or adaptable components.

It is calculated that 40 ATIF's are required in the System and with approximately 1,500 corridor modules required for the entire project, 1,460 welded frames as shown in figure 2 are saved. Also the ATIF's can be re-used on other projects or their steelwork recycled for other uses. The modules are assembled and pressure tested in sets of five on a production line at the manufacturing centre which proves connectivity and alignment. Four are delivered for a day's assembly on site with one remaining. The remaining module is then used with the next four which are assembled to prove connectivity and alignment; this and three from the new set are then delivered to site, and so on. Fundamentally each module is a standard platform (the ATIF and bracketry), with the components within it (pipes, cable containment etc.) being configured specifically to the requirements of the space it serves. Such a strategy provides mass customization. The components selected are push-fit, crimp or clamp type pipe systems, and cable trays (basket type) that connect together also with quick fit couplings. Branch pipes for onward distribution into rooms end with a valve for quick connection to distribution into the adjacent rooms. Pipes, once tested, are insulated at the manufacturing centre with the exception of joints and valves which are insulated on site, once system testing is complete. Riser modules are also assembled at the manufacturing centre and these are single storey risers containing pipe work, ductwork or electrical components, or any combination of the three. A steel riser floor is cast-in to the concrete slab as these progress, with each pipe, duct or bus-bar opening pre-cut and capped off, which is removed just prior to the riser being positioned. Where risers are not heavily populated with M&E services, these are assembled onsite using pre-assemblies and kits of associated parts. Plantroom components such as pump sets, pressurization units, valve stations etc. are grouped together and assembled offsite into plantroom modules by the company. These are also wired and insulated at the manufacturing centre to further reduce the amount of work on site. Interconnections between plant modules and risers are site assembled also using pre-assemblies and kits of associated parts.

CONSTRUCTION ZONE COMPONENT FLOWS (TYPE B AND C PARTS – MTO AND MTS)

The approach to manage the flow of components to the point of use has been described earlier in this paper, which is to kit the specific parts for the MEP operation and postpone its delivery until it is needed. The kitting itself is carried out using MTO and MTS suppliers as re-packing centers and de-coupling points. Bertelsen et al. (2006) describe previous experiments using this approach. Each of the components is selected to be quick-fit, commercially available and tried and tested technology. Small pipe work for water and drainage is either push-fit, crimp-fit or clamp type. Larger pipes are welded and flanged, but made offsite. Electrical trays are basket, trunking or ladder type which fit together quickly with snap-on couplings. Power cables for small power and lighting is a modular plug-and-play connectable system configured on site from standard MTO components. Larger armoured cables for main power supplies are standard type MTS and delivered on large cable drums. Low voltage cables (data, BMS, nurse call etc.) are also standard items on small drums or boxed as appropriate. Where components can be assembled together operatives and tools are provided at the local supplier's branch to pre-form conduits and assemble pipe clips onto brackets and the like. Each of these components are delivered to site in purpose made roll cages or similar, with kits offloaded from the point of delivery and delivered to the point of use by a logistics team trained in manual handling methods, thereby avoiding the need for installation team members to do this.

LABOR AND ASSOCIATED COST FORECAST

Combining offsite modular assembly and postponement with the Lean site operations component of the Construction System and projecting the labor required to perform the planned operations forecasts a 35% reduction of onsite labor. This forecast is derived from a comparison of calculated estimates of labor times between conducting the work using traditional methods and by using the Construction System as described in this paper. For all MEP processes, including plantrooms, the traditional method is estimated at 202,800 hours, with the construction method estimated at 131,840[51] hours. This equates to a difference of 70,960[52] hours between the two methods; a 35% reduction. Also, because of the simplification of the assembly process, a lower ratio of skilled to semi-skilled operatives is required, which reduces the average hourly cost of labor. This will further reduce the outturn labor cost of the project. A reduction in total cycle-time is also achieved using the System however, at this stage of research this is kept as a time buffer between M&E construction and commissioning. The reduction in forecasted labor does not represent an overall forecasted labor saving, as work has shifted offsite for modular assembly; it represents a reduction in labor onsite.

The sub-process within MEP1, corridor modules (ATIF's) has been evaluated (once the work was complete) and reported in Court et al. (2008). Here 1,568 actual onsite hours were required elevating and connecting together a total of 196 modules, compared to 22,320 hours estimated using traditional methods with various trade teams completing the required work all working at height; a 93% reduction. An 8.62% cost benefit is also reported. This cost

[51] Corrected from published paper as printed. This is printed as 131,040 hours and should read 131,840 hours (authors tying error).

[52] Corrected from published paper as printed. This is printed as 71,760 hours and should read 70,960 hours (authors tying error).

analysis compares an estimate of traditional method against actual offsite method including: basic materials; material waste; labor including supervision and testing; productivity losses; transport costs; site equipment; rectification and rework costs and design costs. Productivity losses means a cost factor estimate of the productivity losses possible between the different methods, including weather, stoppages, damage, theft and interferences etc. The estimated cost of this has been assessed as 25% of traditional installation labor only to demonstrate this variable. As the paper reports, the value of this variable provide the cost benefit assessed between the different methods. In other words, if estimated productivity losses for the traditional method were zero percent, then there would be no cost benefit of the offsite method; but this is unlikely in the opinion of the authors and according to previous research (Hawkins 1997). This measured average overall productivity as 37% on the UK projects monitored. In essence, the increased offsite costs for manufacturing centre overhead, additional transport and assembly drawings are more than offset by the higher onsite costs related to productivity, supervision, site testing and rework. When this benefit has been combined with the results emerging from the implementation of the Construction System through all MEP processes, a final analysis against overall forecasted benefits will be made and reported in future research papers.

CONCLUSION

This paper has presented the outcome of an engineering study (and certain results) as part of the design and development of a Lean and agile Construction System and in particular its supply chain component combining modular assembly with a postponement function for a designated building phase within a case study project. The Construction System component described in this paper has been developed as a specific set of countermeasures to overcome what would otherwise occur had these interventions not been made. Modular assembly using mechanical lifting aids will significantly reduce the risk of manual handling injury to workers. It will need fewer operatives to carry out the simpler assembly tasks required and risk of injury is reduced by having fewer workers operating at height. It is also a method to avoid symbiotic relationships that would otherwise exist which will increase the performance of crews carrying out their operations. Congestion on site will be reduced which itself will eliminate the generation of hazards and increase the output of workers. Productivity will be improved because less work is required on site by workers cutting, drilling, assembly and elevating parts into position using traditional methods. Furthermore, a significant gain in installation performance will be achieved as the System has adopted innovative quick-fit components and systems. Postponing kits of parts offsite until the time they are needed will avoid the poor site storage and handling strategies that BSRIA report which have shown to be the cause of delays and lost productivity in UK M&E construction. By managing the flows of components in this way will enable trades to perform their operations as planned avoiding potential trade stacking and out of sequence working that has been seen to occur. This research has forecast that a reduction of 35% of onsite labor can be achieved and a lower skill mix is required to perform the simpler assembly tasks as a result. A further benefit of this is that the company avoids the potential risk they face due to the shortage of trained workers available in UK construction, with the lower skill mix resulting in a reduced average labor cost on the project. Whilst certain elements of what has been described in this paper are common practice in the UK M&E industry, the authors believe that the contribution to research is the combination of countermeasures described that have been incorporated into a wider Construction System, in the same way that manufacturing has used this strategy. Also by developing an innovative method for assembling, transporting and installing corridor and riser modules, using an ATIF, modularization can be achieved with or without offsite manufacturing capability. In fact, this approach can be adopted by M&E contractors on site, but off-line. Space permitting, a small assembly workshop can be set up adjacent to a construction site to carry out this process, or supply chain partners can be developed and encouraged to use this method. Also, parts-kitting can be achieved by the supply chain according to the principles set out in this paper. If distances for transportation are too great, then again this function could be carried out on a construction site, but not at the point of use, as is traditionally seen. This should be done off-line by a logistics team, and not by the workers themselves. This Construction System component presents a set of countermeasures that are designed to overcome what traditionally occurs on UK construction sites as this research paper has described and to meet the stated research project objectives; which is to design a way of working on site for improved health, safety and productivity for the company.

FURTHER RESEARCH

The next phase of research will be to test the Construction System and measure the results emerging from the implementation on a case study project. This will be for the M&E work associated with the Maternity and Oncology Centre, a phase within the case study project. This implementation phase will test the System by measuring the expected benefits which is to avoid the risk of incidents or injury to workers, have less workers onsite carrying out simpler assembly tasks, and with improved productivity to maintain the labor cost centre budget thereby defending the company's margin on the project (Court et al. 2005).

REFERENCES

Ballard, G. and Matthews, O. (2004). Championship – prefabrication and assembly. Proc., Twelfth Annual Conf. of the Int. Group for Lean Construction (IGLC-12), Elsinore, Denmark, 625-628.

Bertelsen, S., Koskela, L., Henrich, G., and Rooke, J. (2006). Critical flow-towards a construction flow theory. Proc., Fourteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-14), Santiago, Chile, 31-40.

Burbidge, J.L. (1996). Period batch control, Oxford University Press, New York, USA.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D. (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects." Proc., Thirteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-13), Sydney, Australia, 3-11.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D. (2006). Design of a Lean and agile Construction System for a large and complex mechanical and electrical project. Proc., Fourteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-14), Santiago, Chile, 151-164.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D. (2007). Transforming traditional construction into a modern process of assembly using Construction Physics. Proc., Fifteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-15), Lansing, USA, 345-356.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D. (2008). Modular assembly in healthcare construction – a mechanical and electrical case study. Proc., Sixteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-16), Manchester, United Kingdom, 521-531.

Fredriksson, P. (2006). Mechanisms and rationales for the coordination of a modular assembly system – the case of Volvo cars. Int. J. of Ops. and Prod. Manage., Vol 26 No. 4, 350-370.

Forza, C. (1996). Work organisation in Lean production and traditional plants – what are the differences? Int. J. of Ops. Manage., Vol. 16. No. 2, 1996, 42-62.

Gibb, A.G.F. (2006) (Keynote). Occupational health: slow accidents need solutions fast, in Fang, Choudry & Hinze (eds), Global Unity for Safety & Health in Construction, Proc., of CIBW99 Int. Conf., June 2006, Beijing, Tsinghua University Press, 22-33.

Goodier, C.I., Gibb, A.G.F. (2005). Barriers and opportunities for offsite in the UK. Systematic Innovation in the Management of Projects and Processes. Abdul Samad Kazi (ed), cib Helsinki international joint symposium, 148-158.

Granath, J.A. (1998). Torlanda to Uddevalla via Kalmar: a journey in production practice in Volvo. Seminário Internacional Reestruturaçã Productiva, Flexibilidade do Trabalho e Novas Competências Profissionais, COPPE/UFRJ, Rio de Janeiro, Brasil.

Hawkins, G. (1997). Improving M&E site productivity. BSRIA technical note TN 14/97, The Building Services Research and Information Association, Bracknell, UK.

Hawkins, G. (2002). Site Productivity – 2002. A guide to the uptake of improvements. BSRIA technical note TN 13/2002, The Building Services Research and Information Association, Bracknell, UK.

Health and Safety Executive (2000). Backs for the future: safe manual handling in construction. HSE books, Norwich, UK.

Health and Safety Executive (2007). Health and safety in the construction industry. <http://www.hse.gov.uk/construction/index.htm> (Mar. 4, 2007).

Health and Safety Executive (2007a). Better backs in construction. <http://www.hse.gov.uk/construction/backs/index.htm> (Mar. 4, 2007).

Health and Safety Executive (2007b). Musculoskeletal disorders – HSE and MSD's. <http://www.hse.gov.uk/msd/hsemsd.htm> (Mar. 4, 2007).

Hopp, W. J., and Spearman, M. L. (2001). The MRP crusade. Factory physics, 2nd Ed., Irwin/McGraw-Hill, New York, USA, 109-150.

Horman, M. J., Orosz, M. P., and Riley, D. R. (2006). Sequence planning for electrical construction. J. Constr. Eng. Manage., 132(4), 363-372.

Liker, J. K. (2004). The Toyota Way: 14 management principles from the world's greatest manufacturer, McGraw-Hill, New York, USA.

Pasquire, C.L., and Connolly, G.E. (2002). Leaner construction through off-site manufacturing. Proc., Tenth Annual Conf. of the Int. Group for Lean Construction (IGLC-10), Gramado, Brazil, 263-275.

Pasquire, C.L., and Connolly, G.E. (2003). Design for manufacture and assembly. Proc., Eleventh Annual Conf. of the International Group for Lean Construction (IGLC-11), Blacksburg, Virginia, 184-194.

Skipworth, H., and Harrison, A. (2004). Implications of form postponement to manufacturing: a case study. Int. J. Prod. res., 15 May 2004, vol. 42, no. 10, 2063-2081.

Thomas, H. R., Horman, M. J., and de Souza, U. E. L. (2004). Symbiotic crew relationships and labor flow. J. Constr. Eng. Manage., 130(6), 908-917.

Ulrich, K. T., Eppinger, S. D. (2004). Product architecture. Product design and development, 3rd Ed., McGraw Hill, New York, USA, 163-186.

Wilson, D. (2000). Innovative M&E installation. BSRIA ACT 9/2000, the Building Services Research and Information Association, Bracknell, UK.

Winch, G. M., and North, S. (2006). Critical space analysis. J. Constr. Eng. Manage., 132(5), 473-481.

Yang, B., and Burns, N. (2003). Implications of postponement for the supply chain. Int. J. Prod. res., 2003, vol. 41, no. 9, 2075-2090.

APPENDIX D PAPER 4 (REFEREED, CONFERENCE)

Court, P., Pasquire, C., Gibb, A.G.F., (2008). Modular assembly in healthcare construction – a mechanical and electrical case study. Proc., Sixteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-16), Manchester, United Kingdom, 521-531.

MODULAR ASSEMBLY IN HEALTHCARE CONSTRUCTION – A MECHANICAL AND ELECTRICAL CASE STUDY

Peter Court, Dr. Christine Pasquire, Prof. Alistair Gibb

ABSTRACT

This paper presents findings as part of a research project to develop and implement a Lean and agile Construction System on a case study project. The objective of the research project for the sponsor company is to improve its projects site operations, making them safer for the worker, and improving efficiency and productivity. A principle output of the research is the development and use of an innovative method for assembling offsite, transporting and installing mechanical and electrical distribution modules. In total 196 modules were installed in 17 construction zones on the case study project and the results show that zero accidents occurred either onsite or offsite associated with this work; an 8.62% cost saving is achieved over an estimation of traditional methods (with an estimated productivity loss of 25% for traditional method site labour); a higher quality is achieved with less site rework; 93% less hours are required onsite for the S&P method (much fewer operatives onsite at risk of injury); and a shorter overall cycle-time is required to complete the work when compared to traditional methods.

This paper reports on the findings using IMMPREST software as a tool for assessing the benefits derived from the use of modular offsite assembly for this case study.

KEY WORDS

Construction System, IMMPREST, health, safety, productivity.

INTRODUCTION

This is a practical paper drawn from a collaborative research project (the research project) being undertaken at the Centre for Innovative Collaborative Engineering at Loughborough University, UK. The programme is funded by the Engineering and Physical Sciences Research Council (EPSRC) and is sponsored by a major UK mechanical and electrical contractor (the company). The research project has specific objectives, which will be capable of making a significant contribution to the performance of the sponsor company.

The company is developing a Construction System in order to improve the performance of its projects, and earlier research in this field (Court et al. 2005) has shown that Lean interventions when applied to a case study project had positive results. The next phase of the research (Court et al. 2006, 2007), using leading edge research and learning, designed a Lean and agile Construction System which is to be implemented on a major private finance initiative (PFI) hospital development, and in particular the mechanical and electrical (M&E) elements within it (the case study project). This paper reports on the findings from the implementation of a component of the Construction System, the offsite modular assembly of corridor mechanical and electrical distribution services using assembly, transportation and installation frames (ATIF's), described in Court et al. 2007. This case study uses using the IMMPREST[53] toolkit which Pasquire et al. (2005) describe as a tool for assessing the benefits derived from the use of modular offsite assembly against what would have been traditional installation methods. The benefits are classified into six categories and these are cost; time; quality; health and safety; sustainability and site benefits.

[53] Interactive Model for Measuring Preassembly and Standardisation in construction.

RESEARCH PROJECT OBJECTIVES

The objective of this project for the company is to improve site operations, making them safer for the worker and to improve productivity as a countermeasure to the prevailing conditions in UK construction and the company itself. Safety is at the core of the company and according to the Business Leaders *"…it is an absolute right for people to return home safely at the end of a productive day's work,"* and *"failure to do so renders the company valueless."* The key words here being *safely* and *productive,* these are therefore the key objectives of this research project, which is to design and implement a way of working on site, the countermeasures, that will satisfy these objectives.

THE CONSTRUCTION SYSTEM

The Construction System is the methodology to deliver the objectives of the sponsor company and is represented in figure 1. Its underpinning theory incorporates manufacturing concepts such as modular assembly, postponement, reflective manufacture, pulse-driven scheduling and ABC parts classification (Court et al. 2006). The System is designed with Lean and agile concepts to specifically eliminate waste from M&E (and key interfacing trades) construction activities (the Lean dimension). The agile dimension is designed to provide each trade team exactly what they want, when they want it and where they want it. These Lean and agile attributes are designed to standardise the work, process and products to create flow, pull and value delivery. The ergonomic and workplace organisation attributes are designed to specifically improve workers health, safety and productive output (Court et al. 2005). Its key components are its supply chain with a postponement function and its site operations. The supply chain component has been categorised using ABC parts classification with modules (type A) being delivered directly to site on a call-off system. Components and consumables (type B and C) being parts kitted or replenished for delivery to site via the postponement function also on a call-off system and to the exact requirements for the site operations. The kits are to be postponed until the moment they are needed. Site operations are conducted by trade teams (T1, T2 etc.) using mobile work cells and ergonomic access equipment (Court et al. 2005). The System operates using a pulse-driven system which has been called the Week-Beat.

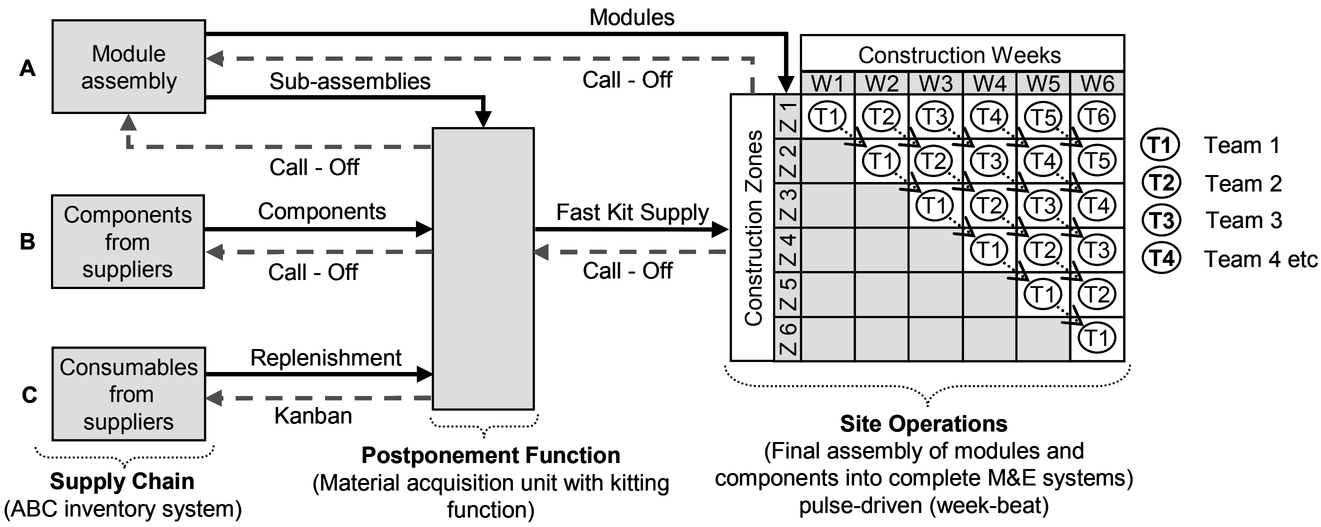

Figure 1 The Construction System (from Court et al. 2007)

As described, the Construction System has been specifically designed as a set of countermeasures to overcome the historically poor health, safety and productivity issues facing the construction industry today. The Health and Safety Executive (HSE 2007), report that in the last 25 years over 2,800 people have died from injuries they received as a result of construction work, with many more injured or made ill. Further research (HSE 2007a) has identified that construction has the highest rate of musculoskeletal disorders (MSD's). These are mostly back injuries from manual handling. In their research into MSD's, the HSE (2007b) have indentified areas that create risk, which include; repetitive and heavy lifting; bending and twisting; repeating an action too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment;

psychosocial factors (e.g. high job demands, time pressures and lack of control); not receiving and acting upon reports of symptoms quickly enough.

Considering other health and safety factors, occupational health has been ignored in favour of the more immediate, high impact occupational safety (Gibb 2006). Gibb argues that occupational health incidents are to be considered as “slow accidents” – the period over which the incident occurs may be lengthy and may creep up on you unawares. Gibb’s keynote paper reports that in the UK 4,500 construction workers are absent from work every day because of injuries caused by accidents, but there are 11,000 construction workers off sick at any one time with a work-related illness. Research conducted for its better backs campaign, the Health and Safety Executive (HSE 2000) found that a change to prefabricated modules for mechanical and electrical works and the use of mechanical aids to lift them significantly reduced the risk of manual handling injury. This enabled employees to maintain an improved posture when connecting and testing the units.

An investigative study by the Building Services Research and Information Association (BSRIA) set a foundation for understanding the problems and issues that the UK M&E industry faces within the construction sector (Hawkins 1997). Significantly, the UK projects monitored had an average overall productivity of only 37% when compared to observed best practice and an average task productivity of only 56% by comparison. Subsequent research conducted by BSRIA (Hawkins 2002) concluded that UK construction project teams that implemented improvement strategies and actions in accordance with the BSRIA best practice recommendations have realised significant improvements in site productivity. The research found that teams that designed for high site productivity used innovative components and exploited offsite manufacture realised a step-change improvement in construction site productivity rates. Modular assembly is also a method recommended to overcome symbiotic crew relationships (Thomas et al. 2005). These relationships exist where the pace of a crew depends on the pace of a preceding crew and that the performance of crews with symbiotic relationships is shown to be consistently worse than when these relationships are not present. The ATIF's are a component of the Construction System specifically designed as a countermeasure to overcome these construction issues that would otherwise occur on the case study project.

APPLICATION OF THE CONSTRUCTION SYSTEM

The Construction System is being applied on each phase of a case study project the first being a new Maternity and Oncology Centre (Court et al. 2007). Earlier work for this research project has described how the parts to be used that form the complete M&E systems on the case study project were categorised using ABC parts classification, with type A being modules, type B being loose components and type C being consumables such as nuts, bolts, washers and the like. Described also was the research involved in setting the supply chain strategy. This is to pre-assemble as much as possible offsite (type A parts) to be delivered Just-In-Time and incorporated into the final assembled systems along with component kits (type B and C parts) in a series of small and simple tasks. In Court et al. 2007 it was described how the mechanical and electrical works (MEP1-5) and building fabric works (BFP1-6) were sequenced within an agreed assembly process and within MEP1 a sub-process is the installation of corridor modules. This is shown in figure 2. These modules are made offsite at the company's manufacturing centre which has been producing modular M&E assemblies since the mid 1990's and has previously been the subject of research studies (Pasquire and Connolly 2002; Mawdesley and Long 2002; Pasquire and Connolly 2003). The authors believe that the contribution to research is how modularisation can be incorporated into a wider Construction System in the same way that manufacturing has used this strategy.

Also, by using an innovative method for assembling, transporting and installing corridor and riser modules elements of modularisation can be achieved with or without offsite manufacturing capability.

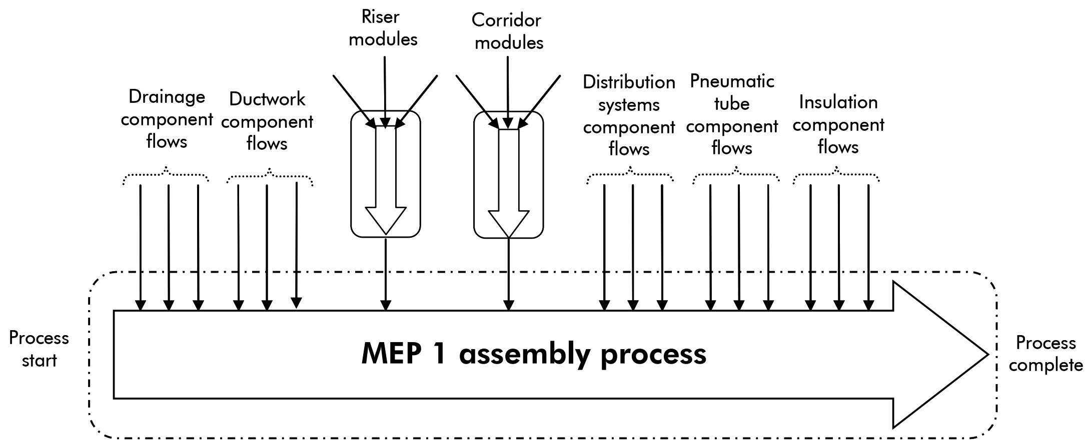

Figure 2 Mechanical and electrical process 1 (from Court et al. 2007)

MEP1 – CORRIDOR MODULES

The initial corridor module design used a rigid welded unistrut steel frame which contains the M&E components within it. However, once the module has been installed, most of the steel frame is redundant, therefore not adding value to the module other than during assembly and transportation from the place of manufacture (manufacturing centre). This adds cost to the module, which has been seen as a barrier to offsite manufacture (Goodier and Gibb 2005). To overcome this, an assembly, transportation and installation frame (ATIF) was conceived. Here modules are assembled in the manufacturing centre, transported to site, incorporated into the building using mechanical hoists with the ATIF returning to the manufacturing centre for re-use. Figure 3 demonstrates digital prototypes of three stages of this sub-process. The modules when lifted on the ATIF are bolted to cast-in unistrut inserts running in tram-lines along corridor positions in the concrete soffit. This avoids the need for workers drilling for fixings into concrete, reducing the risk of injury from hand-arm vibration.

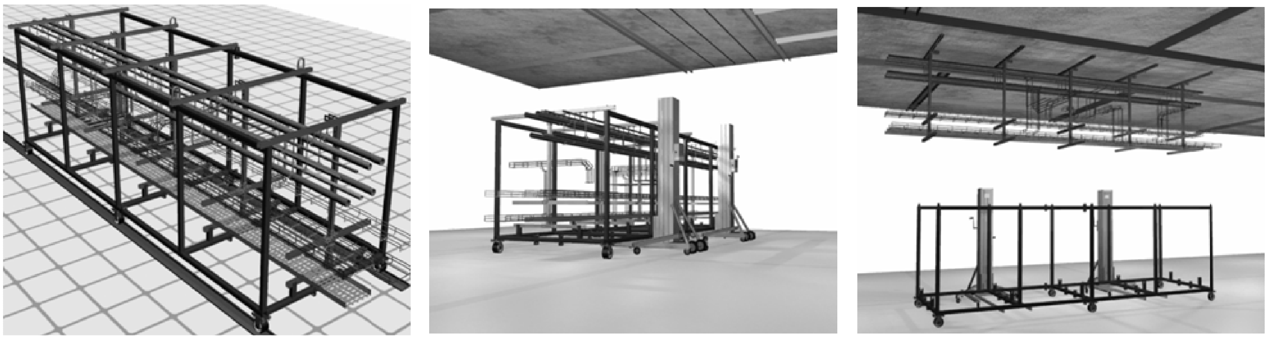

Figure 3 ATIF ready in manufacturing centre; onsite ready for elevation using mechanical lifting hoists; corridor module installed with ATIF to be returned to manufacturing centre for re-use

The modules and ATIF's have been standardised during the design process, in that there are two corridor widths and two corridor ceiling void heights giving four size combinations. The ATIF is designed to accommodate each of these four sizes by being reconfigurable via removable or adaptable components. It is calculated that 40 ATIF's are required in the System and with 1,500 corridor modules required for the entire project, 1,460 welded frames are saved. Also the ATIF's can be re-used on other projects or their steelwork recycled for other uses. For the Maternity and Oncology phase of the project, a total of 196 ATIF corridor modules were used in 17 construction zones (average of 12 per zone). With each module being 6 metres long, this represents a total linear corridor length of 1.176 kilometres. Table 1 represents the total contents of all modules that would have been fitted onsite in a traditional manner had the modular method not been used.

Table 1 ATIF statistics – Maternity and Oncology building

Quantity	Copper and Steel pipework	Valves and fittings	Electrical containment
196 ATIF's containing 980 pre-assembled brackets	7,762 metres, size range 15 – 108mm; associated thermal insulation	1,273 valves (isolation; commissioning; control valves etc.); 8,650 fittings (elbows; bends; reducers etc.)	5,139 metres basket tray, size range 100 – 300mm wide

RESULTS

The planned onsite resource to elevate and install the modules is one pair of operatives from the duct fitting team. To connect modules together was also one pair of operatives from the composite pipework and electrical installation team.

This paper reports on the findings from this case study using the IMMPREST toolkit. Pasquire et al. (2005) describe the IMMPREST toolkit as a tool for assessing the benefits derived from the use of modular offsite assembly (hereafter known as S&P[54]) against what would have been traditional installation methods. The benefits are classified into six categories and these are cost; time; quality; health and safety; sustainability and site benefits. The traditional option described in the assessment is: site installation of corridor mechanical and electrical services using traditional methods (known hereafter as traditional) and the S&P option described is: modularising corridor services using the ATIF method.

Cost Benefit Summary

The IMMPREST detailed cost worksheet analyses benefits in three areas; construction/manufacturing costs, project costs and life-cycle costs. Overall, the detailed cost worksheets (construction/manufacturing and project costs together) show a benefit in favour of S&P of 8.62%. This is shown in table 2.

Basic material cost for S&P is higher due to offsite manufacturing centre overhead. This also includes an amortised cost allowance for the use of the ATIF frames, considered as an asset to the total project. Actual basic material cost for both methods is considered equal. Material waste for traditional is estimated higher than S&P due to increased probability of site wastage

[54] S&P meaning standardisation and preassembly as an IMMPREST term.

onsite. Traditional labour cost is estimated using installation times guide (Luckins 2003, 2004) using a bill of materials from the S&P manufacturing drawings. The Luckins times guide assumes average times under average conditions, installing good quality materials with good quality trained workmanship. No other site difficulty factors are included. S&P labour cost is actual cost and includes manufacturing centre overhead and the onsite cost to install modules and connect them together.

Table 2 Comparison of estimated traditional costs to actual S&P costs (values are £000's)

IMMPREST Items (by exception)	Traditional (estimated)	S&P (actual)
Basic materials	£197.09	£260.42
Material waste	£15.86	£3.96
Labour including supervision and testing	£273.67	£205.81
Productivity losses (25% of labour only)	£53.12	£0
Transport costs	Included	£44.84
Plant and access equipment	£40.80	£4.08
Rectification and rework	£10.62	£1.28
Design (assembly drawings)	£0	£19.80
Total	£591.16	£540.19
Variance: Traditional to S&P	**£50.97 (8.62%)**	

Productivity losses means a cost factor estimate of the productivity losses possible between the different methods, including weather, stoppages, damage, theft and interferences etc. The estimated cost of this has been assessed as 25% of traditional installation labour only to demonstrate this variable. As can be seen, the value of this variable provides the benefit assessed between the different methods. In other words, if estimated productivity losses for the traditional method were zero percent, then there would be no cost benefit of S&P; but this is unlikely in the opinion of the authors and according to previous research (Hawkins 1997).

This measured average overall productivity as 37% on the UK projects monitored. Any actual cost for S&P loss of productivity is included in the S&P labour cost.

More plant and equipment is estimated for the traditional method and is required for each trade cycling through the site carrying out their work. Transport costs for traditional method is included in basic material costs, with much higher actual cost necessary for S&P. This is required to deliver the ATIF modules from the manufacturing centre to site; and then a back-haul cost to return ATIF's to the manufacturing centre for re-use. Assembly drawings are required for the S&P method for manufacturing purposes; these are not required for the traditional method.

The life-cycle summary did not show any significant benefit from S&P as the categories analysed were either similar or moderately better than a traditional approach.

TIME BENEFIT SUMMARY

The IMMPREST detailed time worksheet analyses benefits in two areas; offsite and pre-construction activities, and onsite activities. For offsite and pre-construction activities a zero percent benefit with moderate confidence is reported. This zero benefit is a result of equal durations for all pre-construction phases of the project. Whilst an additional week per construction zone is required for ATIF module assembly drawings driven from the 3D model, this is offset by the work required to produce paper-space drawing for a traditional onsite method. These would require time to add setting out and invert dimensions and the like. Further to this lead-in times for offsite manufacture of ATIF's is one week, as these are simple assembly processes of pre-made components into the assembly frame. Lead-in times to acquire site materials would also be one week.

For onsite activities, the summary shows a time benefit in favour of S&P with high confidence. Here, total site establishment is considered equal, as the start and end project date remains the same. A benefit is derived from shorter overall cycle-times to install ATIF modules versus the traditional method. The quantity of ATIF's per construction zone is 12 (average), and these are installed within the Week-Beat allocation. With 17 construction zones, a 17 week overall cycle-time is required. Whilst the traditional method would utilise a Week-Beat method, more onsite trades are required to cycle through each construction zone to complete their work, therefore taking longer. This has been estimated as follows: one week bracket assembly; three weeks pipe work assembly including one week testing; one week pipework insulation; and one week electrical containment installation. Overall cycle-time for the traditional method is five weeks, giving an overall cycle time for 17 construction zones of 22 weeks (using a Week-Beat method). Finally, an additional week per construction zone is required to site test the traditional method, whereas the ATIF modules are tested offsite, this also provides a benefit.

QUALITY BENEFIT SUMMARY

The IMMPREST detailed quality worksheet analyses benefits in two areas; construction/manufacture quality and life-cycle quality. For construction/manufacture quality the assessment found that the project should benefit from an S&P approach with high confidence. The main drivers for this benefit (by exception) are; for category relating to the level of quality a significantly better grade of finish and degree of certainty of product quality was found. For the defects and damage category a significantly lower level of defects (failure to achieve the specifications, or damage to the product before final completion) was found. For customer requirements category; a significantly better visual appearance of the finished product and significantly lower level of customer / user complaints was found. The life-cycle summary did not show any significant benefit from S&P as the categories analysed were either similar or moderately better than a traditional approach.

HEALTH AND SAFETY BENEFIT SUMMARY

Firstly, there were zero accidents (minor or reportable) associated with this work, either onsite or offsite at the manufacturing centre. The IMMPREST detailed health and safety worksheet analyses benefits in two areas; construction/manufacture health and safety and life-cycle health and safety. For construction/manufacture health and safety it was found that the project should benefit from the S&P approach with high confidence. The biggest driver for improved health and safety with S&P is the fewer persons (H&S ratios category) required onsite to install and connect together the ATIF modules. In total S&P required 1,568 mans hours onsite, compared to 22,320 man hours estimated for traditional, all working at height (safety category – persons working in difficult or dangerous conditions). This equates to 93% less hours onsite using the S&P approach instead of the traditional. Finally, S&P has significantly lower housekeeping issues; the degree to which activity and process contributes to site waste and untidiness.

Life-cycle summary did not show any significant benefit from the S&P approach as the categories analysed were either similar or moderately better than a traditional approach.

SUSTAINABILITY BENEFIT SUMMARY

The IMMPREST detailed sustainability worksheet analyses benefits in two areas; sustainability issues and respect for people principles. For sustainability issues, the summary finds that the project may benefit from an S&P approach with high confidence. Most items are similar, for ecological impact and physical pollution; moderately better, for waste and materials; moderately lower, for energy consumption, water consumption and community pollution; and moderately higher, for transport. However, one item was significantly lower, and this was the general impact on the local community, the driver for this being the much reduced level of operatives required on site along with associated car parking in the adjacent residential areas due to limited or no car parking facilities onsite. For the respect for people principles, the assessment found that the project should benefit from S&P with high confidence. The main drivers for the benefit (by exception) are: for safety; a significantly lower risk of reportable accidents for S&P; for working hours (long working hours contribute to accidents, poor morale and efficiencies) and travelling time (travel time has an impact on staff morale, productivity and contributes to road traffic accidents which result in lost time), the assessment was significantly lower for S&P.

SITE BENEFIT SUMMARY

The IMMPREST detailed site benefits worksheet analyses site issues as constraints that are to be assessed as either high, low or none and these are; site space and storage, multi-trade interfaces, skilled labour, access to site (including delivery), live working conditions, movement of units onsite and restrictions (on site work by external parties). The assessment found that all category constraints may be mitigated by S&P with high confidence. The main drivers for this are limited site space available for site storage of materials; a traditional method would require many interfacing trades onsite to undertake the work; shortage of skilled labour (Goodier and Gibb 2005); limited site access (live hospital environment); limited movement of vehicles onsite and restrictions on site work due to local constraints (car parking in adjacent neighbourhoods etc.).

CONCLUSIONS

The IMMPREST assessment undertaken has found that overall the use of ATIF's to modularise corridor mechanical and electrical distribution systems has benefitted the project with high confidence. The primary objective of this research project for the company is to improve site operations, making them safer for the worker, and improving efficiency and productivity. The results have shown that by using ATIF's to modularise corridor services; zero accidents occurred either onsite or offsite associated with this work; an 8.62% cost saving is achieved over an estimation of traditional methods (with an estimated productivity loss of 25% of traditional method site labour); a higher quality is achieved with less site rework; 93% less hours are required onsite for the S&P method (much fewer operatives onsite at risk of injury); a shorter overall cycle-time is required to complete the installation in 17 construction zones, 17 weeks versus 22 weeks (23% reduced cycle-time), with higher confidence in S&P.

The ATIF S&P method therefore has been shown to improve health, safety and productivity for onsite operatives, with much fewer being required, mitigating the further risk that the industry faces with shortage of skilled labour. Finally, cost certainty for this element is achieved because of the known actual offsite costs and much higher certainty of resultant onsite costs. A traditional method would not, in the opinion of the authors, achieve full productivity, therefore whatever productivity loss is estimated, a cost benefit will be achieved with an S&P method. If this method saves health and safety risks, costs less and takes less time, why would you not do it?

FURTHER RESEARCH

Further research is currently being conducted to finalise the implementation of the Construction System on the case study project and to conduct analysis of the overall results, this being the final phase of research. The results emerging from this will be reported in future research papers.

REFERENCES

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2006). Design of a Lean and agile Construction System for a large and complex mechanical and electrical project. Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2007). Transforming traditional construction into a modern process of assembly using Construction Physics. Proceedings of the 15th annual conference of the International Group for Lean Construction, East Lansing, USA, 2007.

Gibb, A.G.F., (2006) (Keynote). Occupational health: slow accidents need solutions fast, in Fang, Choudry & Hinze (eds), Global Unity for Safety & Health in Construction, Proc. of CIBW99 Int. Conf., June 2006, Beijing, Tsinghua University Press, pp. 22-33.

Goodier, C.I., Gibb, A.G.F., (2005). Barriers and opportunities for offsite in the UK." Systematic innovation in the management of projects and processes. Abdul Samad Kazi (ed), cib Helsinki international joint symposium, pp. 148-158, ISBN 952 5004 64 3.

Hawkins, G., (1997). Improving M&E site productivity, BSRIA Technical Note TN 14/97, The Building Services Research and Information Association, Bracknell, UK.

Hawkins, G., (2002). Site Productivity – 2002. A guide to the uptake of improvements, BSRIA technical note TN 13/2002, The Building Services Research and Information Association, Bracknell, UK.

Health and Safety Executive, (2000). Backs for the future: safe manual handling in construction, HSE books, Norwich, UK.

Health and Safety Executive, (2007). Health and safety in the construction industry. <http://www.hse.gov.uk/construction/index.htm> (Mar. 4, 2007)

Health and Safety Executive, (2007a). Better backs in construction. <http://www.hse.gov.uk/construction/backs/index.htm> (Mar. 4, 2007).

Health and Safety Executive, (2007b). Musculoskeletal disorders – HSE and MSD's. <http://www.hse.gov.uk/msd/hsemsd.htm> (Mar. 4, 2007).

Luckins, (2003). Mechanical installation times guide for estimators. Trade Services Information Limited, 2003, England.

Luckins, (2003). Electrical installation times guide for estimators. Trade Services Information Limited, 2003, England. ISBN 0 5912985 3 4.

Mawdesley, M.J., and Long, G., (2002). "Prefabrication for Lean building services distribution." Proc. Tenth Annual Conf. of the Int. Group for Lean Construction (IGLC-10), Gramado, Brazil.

Pasquire, C.L., and Connolly, G.E., (2002). Leaner construction through offsite manufacturing. Proc. Tenth Annual Conf. of the Int. Group for Lean Construction (IGLC-10), Gramado, Brazil.

Pasquire, C.L., and Connolly, G.E., (2003). Design for manufacture and assembly. Proc. Eleventh Annual Conf. of the International Group for Lean Construction (IGLC-11), Blacksburg, Virginia.

Pasquire, C., Gibb, A.G.F., and Blissmass, N., (2005). What should you really measure if you want to compare prefabrication with traditional construction?" Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

Thomas, H. R., Horman, M. J., and de Souza, U. E. L., (2005). Symbiotic crew relationships and labor flow. J. Constr. Eng. Manage., 130(6), 908-917.

APPENDIX E PAPER 5 (JOURNAL, PUBLISHED)

Court, P., Pasquire, C., Gibb, A.G.F., (2009). A Lean and agile Construction System as a set of countermeasures to improve Health, Safety and productivity in mechanical and electrical construction. Lean Construction Journal, November 2009.

A LEAN AND AGILE CONSTRUCTION SYSTEM AS A SET OF COUNTERMEASURES TO IMPROVE HEALTH, SAFETY AND PRODUCTIVITY IN MECHANICAL AND ELECTRICAL CONSTRUCTION.

Peter F.Court, Christine Pasquire, Alistair Gibb

This paper presents certain aspects of the findings of a research project to develop and implement a Lean and agile mechanical and electrical (M&E) Construction System on a case study project. The objective of the research project for the sponsor company is to improve its projects site operations making them safer for the worker and improving efficiency and productivity by overcoming the problems and issues that it faces in the M&E industry within the UK construction sector.

The research finds that using the System on the case study project, and when compared to a traditional method, a 37% reduction in onsite labour was achieved; no time slippage occurred during onsite assembly to delay or disrupt other trades; less workers onsite were exposed to lower health and safety risks from site operations leading to zero reportable accidents; good ergonomics was achieved by focussing on workplace design thus improving workers wellbeing; an improved quality of work was achieved for those required on site carrying out simpler assembly tasks; productivity gains were achieved by eliminating process waste; a 7% direct labour reduction was achieved leading to no labour cost escalation that otherwise could have occurred further reducing the risk of labour cost escalation. Significantly, an overall productivity of 116% was achieved using the Construction System which compares favourably to the Building Services Research and Information Association (BSRIA) findings

of an average overall productivity of only 37% when compared to observed best practice for the projects in that case study research. Also, no compression of the commissioning period occurred with the built facility being handed over to the customer on time.

KEY WORDS Construction System, countermeasures, Last Planner, Health and Safety, productivity.

INTRODUCTION

This is a practical paper drawn from a collaborative research project (the research project) being undertaken at the Centre for Innovative Collaborative Engineering at Loughborough University, UK. The programme is funded by the Engineering and Physical Sciences Research Council (EPSRC) and is sponsored by a major UK mechanical and electrical contractor (the company). The research project has specific objectives, which will be capable of making a significant contribution to the performance of the sponsor company. The research problem that this project is designed to overcome is that of the poor health, safety and productivity performance that the company faces in UK construction. These problems are described in this paper.

The researcher is developing a Construction System for the company to overcome these problems and therefore to improve the performance of its projects. This paper is the sixth in a series of papers reporting on the design and implementation of the System and is a continuation of the already published findings and results of the same methodology and case study project. This paper presents the health, safety and productivity findings measured as the outcome of implementing the System on the case study project during the sample period. As a point of note, the researcher is the M&E Project Leader for the company on the case study project and is submitting these papers as part of the award for an Engineering Doctorate being studied at Loughborough University in the United Kingdom.

RESEARCH PROJECT OBJECTIVES

As stated the objective of this project for the company is to design and implement a new way of working on site to improve site operations, making them safer for the worker and to improve productivity. Safety is at the core of the company and according to the Business Leaders *"…it is an absolute right for people to return home safely at the end of a productive day's work,"* and *"failure to do so renders the company valueless."* The key words here being *safely* and *productive,* these are therefore at the core of this research project, which is to design and implement a way of working on site that will satisfy these objectives by overcoming the problems and issues that it faces.

UNDERPINNING PURPOSE

The purpose of designing and implementing this Construction System is to specifically understand and to overcome the issues that face M&E construction in terms of historically poor health, safety and productivity outcomes on projects. The System is a specifically designed construction methodology to act as a set of countermeasures[55] to what would otherwise occur had this not been done. The System accepts existing research into the issues faced in construction (specifically M&E construction) and therefore does not seek to replicate this. Consider it as designing and implementing a new production process for M&E construction using innovative techniques drawn from extensive research, observation, experience, lessons learned, continuous improvement, and new technology. The main issues

[55] A countermeasure is defined by Oxford English Dictionary (2009) as an action taken to counteract a danger or threat. The threat to the company is the primary issues faced in UK construction, i.e. the research problem.

that the System is designed to countermeasure have been discussed in previous research papers together with how the System works to overcome them. These primary issues were identified as an outcome of a thorough literature review and the particular research process undertaken. These are now described.

THE RESEARCH PROCESS

The initial phase of the research process undertaken involved a literature review, observational studies, and ethnography to establish the current state; how things are done today which sets a foundation of understanding the research problem and what to do to overcome it. The key findings of this phase and the issues that the company faces revolve principally around health and safety factors (HSE 2000, 2007, 2007a, 2007b, Gibb 2006); space availability issues (Winch and North 2006, Akinci et al. 2002, 2002a, Guo 2002); productivity issues (Hawkins 1997, 2002, Wilson 2000); crew conflict issues (Howell et al. 1993, Thomas et al. 2005 and Horman et al. 2006) and worker skills issues (Goodier and Gibb 2005). The primary issues and their source are summarised in table 1.

These issues represent the basic underpinning reasons for the company to improve its site operations as it is indeed not immune from these. The next phase of research was conducted to be able to design a set of countermeasures to overcome the issues identified in table 1. This phase focussed on research and learning from manufacturing, and in particular Lean and agile methods in use today. The research and learning undertaken has been used to develop a theoretical Construction System that incorporates manufacturing methods such as modular assembly; postponement; reflective manufacture; pulse-driven scheduling and ABC parts classification.

Table 1 Summary of primary issues

Primary issues	Source
Manual handling injuries caused by repetitive and heavy lifting; bending and twisting; repeating actions too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment and psychosocial factors.	Health and Safety executive (2007a, 2007b).
Slow accidents caused by health factors. The period over which the incident occurs may be longer but the result is the same, a worker gets injured but it takes longer.	Gibb (2006).
Site congestion generates hazards and reduces output.	Winch and North (2006); Akinci et al. (2002a, 2002b); Guo (2002); observational studies; ethnography.
Subcycle and symbiotic crew relationships delay each other.	Howell et al. (1993); Thomas et al. (2004).
Too much site cutting and elevation of parts into position.	Hawkins (1997); observational studies; ethnography.
Poorly conceived materials handling strategies.	Hawkins (1997); observational studies; ethnography.
Very poor levels of housekeeping.	Hawkins (1997); observational studies; ethnography.
Outdated components and processes.	Wilson (2000); Hawkins (2002); observational studies; ethnography.
Site workers in short supply or inappropriately skilled.	Goodier and Gibb (2005).
Limited, unplanned or improvised workplace organisation, workbenches, and equipment.	Observational studies; ethnography.
Assembly work carried out on the floor or on whatever came to hand.	Observational studies; ethnography.
Nowhere to hang drawings or other information.	Observational studies; ethnography.
Scaffold systems provided that had to be accessed by climbing a ladder and opening flaps, with no facilities to store materials or tools.	Observational studies; ethnography.
Tools only provided by the tradesmen - they had what they had irrespective of their suitability.	Observational studies; ethnography.

These manufacturing concepts are described, together with their applicability to the development of the Construction System, in court et al. (2006 and 2007). These methods are summarised in table 2.

Table 2 Summary of manufacturing methods used in the Construction System

Method	Definition
Modular assembly.	The ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then bought onto the main assembly line and incorporated through a small and simple series of tasks.
Postponement.	An approach that helps deliver more responsive supply chains. Form postponement involves the delay of final manufacturing until a customer order is received. When distribution of the product is delayed to the last minute and only configured and distributed when the customer order is received then you have logistics postponement.
Reflective manufacture.	Evolved from Volvo's development of production systems which looked into quality of work as well as efficiency of production. It includes control over methods, time and quality plus the responsibility to plan ahead and the knowledge needed to reflect on work done. Quality of work also means good ergonomics, appropriate working tools and a good working environment.
Pulse-driven scheduling.	Means period batch control (also know as period flow control) which is a Just-In-Time, flow control, single cycle, production control method, based on a series of short standard periods generally of one week or less.
ABC parts classification.	Parts are classified into A Parts - the first 5 to 10 percent of the parts accounting for 75 to 80 percent of expenditure; B Parts - the next 10 to 15 percent of the parts accounting for 10 to 15 percent of expenditure; and C Parts - the bottom 80 percent or so of the parts accounting for only 10 percent or so of expenditure.

These manufacturing methods form the underpinning design of the Construction System, which is now described.

THE CONSTRUCTION SYSTEM

The Construction System is specifically designed as a set of countermeasures to overcome the primary issues that face the company and to deliver the objectives of the sponsor company and is represented in Figure 1. Its underpinning design incorporates manufacturing methods such as modular assembly, postponement, reflective manufacture, pulse-driven scheduling and ABC parts classification. These concepts from manufacturing are described in Court et al. (2006 and 2007). The System is designed with these Lean and agile concepts to specifically eliminate waste from M&E (and key interfacing trades) construction activities - the Lean dimension. The agile dimension is designed to provide each trade team exactly what they want, when they want it and where they want it. These Lean and agile attributes are designed to standardise the work, process and products to create flow, pull and value delivery. The ergonomic and workplace organisation attributes are designed to specifically improve workers health, safety and productive output (Court et al. 2005).

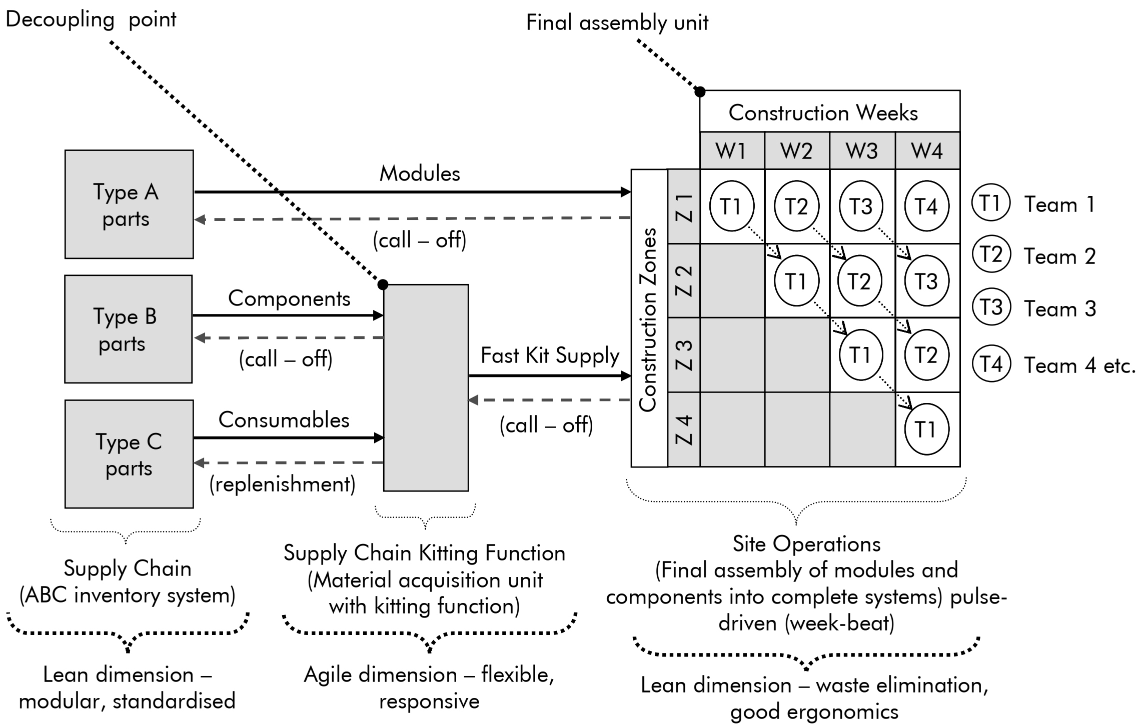

Figure 1 Model of the Construction System (adapted from Court et al. 2007)

Its key components are its supply chain with a postponement function and its site operations. The supply chain component has been categorised using ABC parts classification with modules (type A) being delivered directly to site on a call-off system. Components and consumables (type B and C) being parts kitted or replenished for delivery to site via the postponement function also on a call-off system and to the exact requirements for the site operations (Court et al. 2009). The kits are to be postponed until the moment they are needed. Site operations are conducted by trade teams (T1, T2 etc.) using mobile work cells and ergonomic access equipment (Court et al. 2005). Figures 2 and 3 show typical kit of parts on mobile stillages to be delivered directly to point of use by the logistics team, and mobile work cell in operation for drainage crews.

Figure 2 Kit of parts for ventilation system on mobile stillage

Figure 3 Mobile work cell – drainage crew

The System operates using a pulse-driven system which has been called the Week-Beat (the pulse rate is one week). Here, each team has one week in each construction zone (approximately 1,000 square meters) to complete its work before moving to the next zone and so on. The next team, T2, follows on at the Week-Beat interval, and the next team follows similarly. The Week-Beat method described here is specifically aimed at ensuring that no two or more trades work in the same place at the same time unless allowed to do so, but still separated by physical space. This will prevent crews interfering with each others progress and provide an uninterrupted flow of work in their own clear space without delay.

Another Lean component of the Construction System which is deployed is the Last Planner System (LPS) of production control (Ballard 2000). LPS is a production planning and control tool used to improve work flow reliability. It adds a production control component to the traditional project management system (Henrich et al. 2005). LPS is deployed through each of the phases of the project with six week look ahead's and weekly work plan meetings. LPS has complimentary properties with the Week-Beat method because the six week look ahead's and the weekly work plan meetings screen and shield each weeks planned operations in the Week-Beat using Construction Physics Seven Flows (Bertelsen et al. 2006). These are: information; materials; previous work; space; crews; equipment and external conditions. This drives the team to make ready all the areas of work and using this constraints analysis, only what *can* be done is placed in the weekly work plan. The look ahead is always into the projects strategic programme and measurement of progress is checked back against this which enables corrective actions as required.

As has been described, the Construction System has been designed as a set of specific countermeasures to overcome the issues that exist in construction, as discussed previously. These primary issues together with the Construction System components which act as the countermeasures to them are summarised in table 3.

Having designed the Construction System, the next phase of the research project is its implementation on a case study project. This next phase is now described.

The Case Study Project

The case study project is part of the development of a major acute hospital being procured using the UK Government's Private Finance Initiative (PFI). The project is to be developed in phases across two existing operational hospitals.

Table 3 Issues and Countermeasures

Primary issues	Construction System countermeasures
Manual handling injuries caused by repetitive and heavy lifting; bending and twisting; repeating actions too frequently; uncomfortable working position; exerting too much force; working too long without breaks; adverse working environment and psychosocial factors.	Modular assembly with mechanical lifting aids; trained manual handlers in logistics team; materials in purpose made stillages, trolleys and roll-cages.
Slow accidents caused by health factors. The period over which the incident occurs may be longer but the result is the same, a worker gets injured but it takes longer.	Modular assembly; ergonomic workplace design.
Site congestion generates hazards and reduces output.	Week-Beat (trade separation); mobile work cells; materials in mobile carriers.
Symbiotic crew relationships delay each other. These are tight and closely dependant trades and these are more common in mechanical, electrical, plumbing and finishing trades.	Week-Beat (trade separation).
Poorly conceived materials handling strategies.	ABC parts classification; modular assembly; Just-In-Time parts kitting.
Very poor levels of housekeeping.	Physical waste managed by trained logistics team.
Too much site cutting, drilling, assembly work and elevation of parts into position.	Modular assembly with mechanical lifting aids.
Outdated components and processes.	ABC parts classification; push-fit components; the Construction System; Last Planner System.
Site workers in short supply or inappropriately skilled.	Fewer workers required (modular offsite assembly); lower skill mix needed for simpler assembly tasks.
Limited, unplanned or improvised workplace organisation, workbenches, and equipment.	Workplace organisation; mobile work cells.
Assembly work carried out on the floor or on whatever came to hand.	Workplace organisation; mobile work cells.
Nowhere to hang drawings or other information.	Workplace organisation; mobile work cells; complete with mobile drawing boards.
Scaffold systems provided that had to be accessed by climbing a ladder and opening flaps, with no facilities to store materials or tools.	Ergonomic workplace design; walk-up scaffold systems; scissor lifts.
Tools only provided by the tradesmen - they had what they had irrespective of their suitability.	Appropriate working tools provided for all tradesmen.

The phases are a new Maternity and Oncology Centre (20,000 m² gross internal floor area[56]); Sterile Services Department (2,000 m² gross internal floor area), Hub and Wards Unit (52,000 m² gross internal floor area); Diagnostic Treatment Centre (20,000 m² gross internal floor area); and a Community Hospital – remote location (12,000 m² gross internal floor area).

The project commenced construction in December 2006 (M&E commenced August 2007) and is due for completion in 2012. The major new-build phases of the project are shown in figure 4 (excluding the community hospital phase which is in a remote location five miles away from the main site).

Figure 4 Site layout showing major new-build phases of the project

The Construction System is being applied on each phase of the case study project the first being the new Maternity and Oncology Centre (reported here). This is a 20,000 m² building over four floors. It has electrical and water storage plantrooms in its basement with main ventilation plantrooms over the Oncology Centre at level two and on the roof at level five. Riser shafts are located around the building and distribute air, water, medical gas, electricity

56 Multiply m^2 by 10 for approximate area in square feet.

and the like throughout the building to the various departments. Corridor ceiling voids distribute the services from the riser shafts and then further into individual rooms and spaces, again in the ceiling voids. Finally, services distribute inside dry-lined walls to points of use such as electrical sockets, sinks, basins and bed-head units; everything you would expect to see in a new and modern healthcare facility. The work itself was sequenced using the Week-Beat method with close-scheduling as described in Court et al. (2007). This divided building fabric processes (BFP) into BFP1-6, and mechanical and electrical processes (MEP) into MEP1-5. This being everything required to start and complete all works in a construction zone from a concrete shell to a complete hospital department (in 1,000 m² zones), excluding testing and commissioning.

FINDINGS FROM IMPLEMENTATION

Assembly work commenced on the case study project in August 2007, with planned completion of the installation activities, using the Construction System, at the beginning of October 2008, a 63 week total cycle time including plantrooms (the sample period). This was a target period set and was calculated following a review of the original planned period using a traditional method, and applying this Lean and agile Construction System method to it. This allows a clean commissioning period of 12 weeks (after BFP6 for the final construction zone), with a five week buffer at the end of the programme period. All M&E processes (MEP1-5) and plantrooms were complete at the end of October 2008 (week 66), with the exception of the completion of major customer variations to the Oncology department and working backlog items[57]. These customer variations resulting in approximately 60% of this department (2 construction zones) having to be remodelled. Also, during the sample period

[57] Working backlog is defined here as any minor incomplete works and rework items (such as snagging, missed items of work etc).

(August 2007 to October 2008), 80% of electrical testing was complete; 80% of water systems pressure testing was complete; 50% of extra low voltage system testing was complete (building management systems, fire alarms etc.); 90% of voice and data system testing was complete; and clean commissioning commenced (air and water system balancing). High voltage power-on was achieved June 2008, and water-on to the building was achieved August 2008. Hand-over to the customer occurred in March 2009 for the Maternity facility and June 2009 for the Oncology facility, both on time. The findings are now reported for productivity and labour cost, followed by Health and Safety findings.

PRODUCTIVITY AND LABOUR COSTS FINDINGS

The findings from the implementation have fallen into two sets. The first set was the results and analysis of the benefits from the use of corridor modules in lieu of a traditional installation method. This sub-process, the installation of corridor modules made offsite was evaluated (once the work was complete) and reported in Court et al. (2008). Here 1,568 actual onsite hours were used elevating and connecting together a total of 196 modules, compared to 22,320 hours estimated using traditional methods with various trade teams completing the required work all working at height; a 93% reduction. An 8.62% cost benefit is also reported. The second set combines this benefit with the results from the implementation of the Construction System through all M&E processes and a final analysis against overall expected benefits is now reported. Data collection to enable an assessment of the benefits of the System is presented in figure 5[58]. This presents a comparison of a traditional approach, the Construction System (target Lean and agile) approach, actual hours booked and actual hours booked minus unavoidable delays.

[58] This analysis includes the onsite labour installing ATIF corridor modules described previously.

Curve A is the predicted cumulative labour hours and cycle time for a traditional installation method (for all work including sub-contractors originated from the project cost plan). **202,800 hours with a 69 week cycle time.** This curve is the benchmark against which the Construction System method is measured (planned – curve B, and actual – curves C and D). 202,800 hours is derived from 2,535 pair man weeks which is calculated as follows:

2,535 (pair man weeks) x 2 (men per pair) x 40 (hours per week) = 202,800 hours.

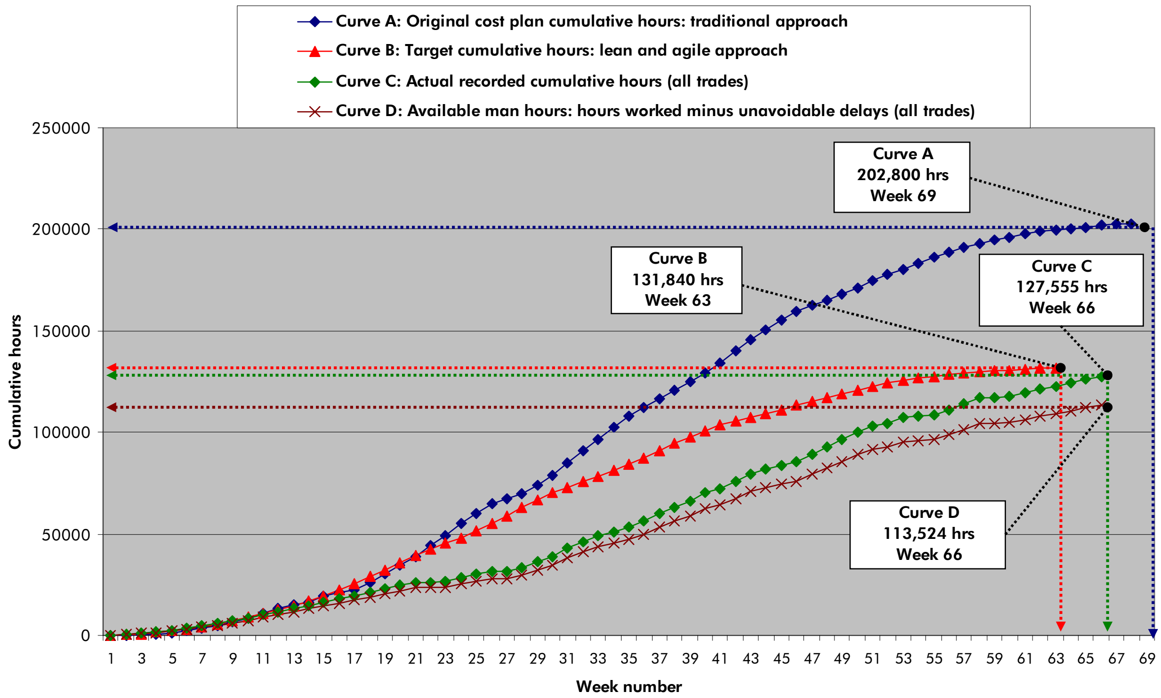

Figure 5 Comparison of traditional approach, target Lean and agile approach, and actual hours booked, with actual hours minus unavoidable delays shown

Curve B is the target predicted cumulative labour hours and cycle time after applying this Construction System method. **131,840[59] hours with a 63 week cycle time.** This is the expected outcome. 131,840 hours is derived from 1,648 pair man weeks which is calculated as follows:

[59] These are paid working hours and therefore already adjusted for unavoidable delays. Workers are paid for a 45 hour week (excluding overtime if worked) and for their lunch break.

1,648 (pair man weeks) x 2 (men per pair) x 40 (hours per week) = 131,840 hours.

Curve C is the actual cumulative labour hours and cycle time recorded during the sample period. **127,555[60] hours with a 66 week cycle time**. This is the actual outcome.

Curve D is the actual cumulative labour hours minus unavoidable breaks. **113,524 hours (unavoidable breaks equate to 11% of actual time) with a 66 week cycle time.**

The onsite assembly finished at week 66 when all work was complete, this is shown as the final point of curve C in figure 5.

Following an analysis of the data, the measured benefits are presented in table 4.

Table 4 Table of Measured Benefits

Curve comparison	Description	Data	Benefit
A to B	The expected benefit (target)	202,800 hours minus 131,840 hours	**70,960 hours (35%)**
		69 weeks minus 63 weeks	**6 weeks**
A to C	The actual benefit	202,800 hours minus 127,555 hours	**75,245 hours (37%)**
		69 weeks minus 66 weeks	**3 weeks**
B to C	Improvement to target	131,840 hours minus 127,555 hours	**4,285 hours (3%)**
		63 weeks minus 66 weeks	**-3 weeks**
B to D	Improvement to target after unavoidable breaks	131,840 hours minus 113,524 hours	**18,316 hours (14%)**
		63 weeks minus 66 weeks	**-3 weeks**

The expected benefit using the Construction System was a 35% reduction in onsite hours and a six week cycle time reduction. The actual benefit achieved using the Construction System

60 These are also paid working hours and therefore already adjusted for unavoidable delays.

was a 37%[61] reduction in onsite hours and a three week cycle time reduction. The actual onsite hours improved from target by 3% (before unavoidable delays) but the expected cycle time benefit of six weeks reduced to an actual of three weeks.

As described earlier this was due to the client changes to the Oncology department which could not be accommodated in the target cycle time period. However, the labour hours for this were absorbed within the actual hours recorded.

As described earlier, Hawkins (1997) reports that the UK projects monitored had an average overall productivity of only 37% when compared to observed best practice. Using the method presented by Hawkins, a similar overall productivity calculation was made. To achieve this, available hours, as defined by Hawkins, were calculated (curve D). This represents recorded actual man hours minus unavoidable delays such as lunch and tea breaks[62]. This represents working hours available.

Overall productivity for the sample period was then calculated using the definition of overall productivity in Hawkins (1997):

$$\text{Overall Productivity} = \frac{\text{Output}}{\text{Available Time}}$$

Where:

- OUTPUT is a measured quantity of installed material to a defined requirement. The physical output is converted to units of time by employing an earned hour's concept based upon best practice installation times.

---

[61] The 37% saving in onsite hours does not represent a saving in labour cost, as these hours contribute to the labour budget for offsite manufactured components.

[62] On average, this is one hour per day per worker: 30 minutes for lunch break; 15 minutes for morning break; and 15 minutes for afternoon break.

- AVAILABE TIME is the total working day minus unavoidable delays such as lunch and tea breaks.

Using this definition and hours from figure 4.42:

$$\text{Overall Productivity} = \frac{131{,}840 \text{ hours}}{113{,}524 \text{ hours}} = 116\%$$

Where:

- 131,840 hours is the total earned hours from the target Lean and agile approach (using best practice installation times – the Construction System).
- 113,524 hours is the booked hours at completion (the sample period) minus unavoidable delays (lunch and tea breaks), tracked using the System.

Therefore, an overall productivity of 116% was achieved using the System, which compares favourably to the BSRIA findings of an average overall productivity of only 37% when compared to observed best practice for the projects in that case study research. This comparison needs to be viewed with a degree of caution, as the calculations shown reflects all of the M&E installations on the case study project compared with BSRIA's findings which represent an average overall productivity for only ductwork, hot and chilled water pipework, and cable management systems. This is treated by the author as a suitable benchmark from which to measure the performance of the Construction System against.

Figure 4 includes time for all labour on site, which is the company's own direct labour and that of its sub-contractors. Of concern to the company was the impact that direct labour cost escalation can have on the projects outturn profitability (Court et al. 2005). Therefore an analysis of the company's direct labour hours was also undertaken.

Table 5 presents a comparison between budgeted direct labour hours (excluding sub-contractor hours) and actual direct labour hours for the sample period (these being the workers actually employed by the company).

Table 5 Budget versus actual direct labour hours during sample period for the Maternity and Oncology case study project

Budget direct labour hours	**Hours**
Budget hours	121,646
Variation hours agreed	11,429
Total budget hours	**133,075**
Actual direct labour hours	
Actual hours booked for the sample period (including supervision and non-productive overtime)	107,973
Further hours to complete (variations and working backlog)	15,680
Estimated final hours at completion	**123,653**
Forecast saving in hours	9,422
Forecast % hours saving	**7%**

It can be seen that a saving in direct labour hours of 7% is achieved using the System. After the sample period, a total of 15,680 hours is reserved to complete customer variations and working backlog items as described previously in this report.

HEALTH AND SAFETY FINDINGS

In terms of safety findings, during the sample period, the case study project had zero reportable accidents, defined as injuries resulting in more than three days off work for the injured party. 19 minor injuries occurred during the sample period however and these were recorded in the company's accident recording system as they occurred. Each accident reported was categorised into accident type; date of accident; primary cause; summary details of accident; underlying causations; behaviours; injured body parts and injury type. An overview of the place of accident, behaviours and primary causes are as follows;

Place of accident: 8 were not at the place work itself; 11 occurred at the place of work.

Behaviours: 2 were non-compliance with procedures; 9 were human error; 7 were personal factors (carelessness, negligence etc.); 1 was a communication failure.

Primary cause: 3 were exposure to a harmful substance; 4 were slips/trips; 1 was contact with plant and machinery; 3 were moving/falling object, 4 were "other"; 4 were handling/lifting or carrying.

Whilst this is not an acceptable result given the interventions made with the Construction System, manual work itself is still at the core of the System and this factor will keep exposing the worker to the risk of minor injury. When studying these results, of particular note was the workers behaviour, all but one of the accidents could have been avoided if the worker complied with procedures, and paid more attention to avoid carelessness. This could be overcome with more routine training given into the behavioural aspects of accident causation. Human error could be reduced with more attention to further error-proofing the installation work itself in the future.

From a health perspective, what benefits did the worker derive from good ergonomics and workplace organisation for their wellbeing? According to Gibb (2006) the often delayed onset of (health) conditions following exposure (to occupational health risks) should drive us to look for solutions and do something about the problems. The interventions made in the Construction System are about providing solutions to the health risks that would otherwise be faced by the workers had these not been made. They are about protecting workers from work related ailments such as MSD's through better management and reduction of their exposure to the causative factors (Gibb 2006). Occupational health is about risk management and in this sense the risk management applied is the workplace organisation implemented in the Construction System by undertaking the following:

- Providing cast-in inserts to avoid the need to drill overhead into concrete for large fixings;
- Providing walk-up scaffolds or scissor lifts to avoid the need to climb ladders inside traditional scaffold systems;
- Providing handling equipment and workbenches to avoid the need to bend over and work or kneel on the floor. This decreases the physical workload of the worker (Sillanpaa at al. 1997);
- Providing modular assemblies with mechanical aids to lift them. This avoids the need to cut and manually elevate components overhead and working at height. This enables employees to maintain an improved posture when connecting and testing the modules (HSE 2000);
- Using mechanical lifting aids generally avoids the need for workers to manually elevate components into position at high level;
- Providing mobile trolleys for tools, components and materials etc. This avoids the need to carry and move things around manually;
- By having all materials stored in mobile trolleys at the workplace, exactly where they are needed. This avoids the need to walk around looking for and carrying things to where you need them;
- By providing simpler assembly tasks with pre-assembled quick-fit components. This avoids workers being engaged in too much site cutting, drilling and assembly work and elevation of parts into final position (Hawkins 1997).

The Construction System was an attempt to reduce the occupational health risks that construction (M&E) workers face and to fit the work to the worker, as far as reasonably practicable. Due to the time lag between the cause and effect in occupational ill health, it was not possible to measure the benefit of these interventions in quantifiable terms within the scope of this research project. Also, without significant medical research and ethical compliance, there was no way of knowing a workers health condition prior to working on the case study project. As such the need would have been to measure over 100 workers physical condition prior to, and after their involvement, in the Construction System during the sample period, and then draw conclusions from the findings. Whilst this was not within the scope of this research project, testing the ergonomic interventions made is an area worthy of further future research. The ergonomic equipment provided will, it is predicted, contribute to a significant reduction in the muscular load on the workers as found by Sillanpaa et al. (1999). What can be said, therefore, is that the Construction System will contribute in reducing the causative problems that lead to work related ailments, and in this sense has workers wellbeing and sending them home safely at the end of a productive days work at its core.

CONCLUSIONS

When compared to the benchmark traditional method 37% less onsite labour was achieved; a three week reduction in construction zone cycle time was achieved, but more significant than this is no time slippage occurring during construction to delay or disrupt other trades, and no compression of the commissioning programme occurred as reported in Dicks (2002), with the built facilities being handed over to the customer on time; 7% direct labour reduction was achieved leading to no labour cost escalation as reported in Court et al. (2005); fewer workers were exposed to lower health and safety risks from site operations leading to zero reportable accidents; good ergonomics was achieved by focussing on workplace design thus improving workers' wellbeing; an improved quality of work was achieved for those on site by carrying out simpler assembly tasks; productivity gains were achieved by eliminating process waste, further reducing the risk of labour cost escalation; a significant overall productivity of 116% is achieved using the Construction System which compares favourably to the BSRIA findings of an average overall productivity of only 37% when compared to observed best practice (Hawkins 1997) for the projects in that case study research (this being subject to the degree of caution mentioned above). Indeed, according to the company, the findings from the Construction System on this case study project, given its size and complexity, far exceed the company's expectations for performance improvement.

FURTHER RESEARCH

The next phase of research will be to continue the validation of the Construction System through implementation and measurement of the results emerging from the final phases of the case study project, this being the Hub, Wards and Diagnostic Treatment Centre, collectively being the largest buildings of the project. Also, a change management methodology is being devised to enable its implementation in these final phases, and further, into the sponsor company's wider organisation. This methodology uses Health and Safety performance as the change driver that the worker commits to through personal choice not just for the sake of it, or because senior management say so.

REFERENCES

Akinci, B., Fischer, M., Kunz, J., and Levitt, R., (2002). Representing work spaces generically in construction method models. J. Constr. Eng. Manage., 128(4), 296-305.

Akinci, B., Fischer, M., Kunz, J., (2002a). Automated generation of work spaces required by construction activities. J. Constr. Eng. Manage., 128(4), 306-315.

Bertelsen, S., Koskela, L., Henrich, G., and Rooke, J. (2006). Critical flow-towards a construction flow theory. Proc., Fourteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-14), Santiago, Chile, 31-40.

Ballard, G., (2000). The Last Planner System of production control. PhD thesis, Department of Civil Engineering, University of Birmingham, Birmingham, UK.

Cassell, C. and Symon, G., (2004). Essential guide to qualitative methods in organisational research. SAGE publications, UK.

Coghlan, D. and Brannick, T., (2003). Doing action research in your own organisation. SAGE publications, UK.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2005). Lean as an antidote to labour cost escalation on complex mechanical and electrical projects. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia, 2005.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2006). Design of a Lean and agile Construction System for a large and complex mechanical and electrical project. Proceedings of the 14th annual conference of the International Group for Lean Construction, Santiago, Chile, 2006.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D., (2007). Transforming traditional construction into a modern process of assembly using Construction Physics. Proceedings of the 15th annual conference of the International Group for Lean Construction, East Lansing, USA, 2007.

Court, P., Pasquire, C., Gibb, A.G.F., and Bower, D. (2008). Modular assembly in healthcare construction – a mechanical and electrical case study. Proc., Sixteenth Annual Conf. of the Int. Group for Lean Construction (IGLC-16), Manchester, United Kingdom, 521-531.

Court, P., Pasquire, C., Gibb, A.G.F., (2009). Modular assembly with postponement to improve health, safety and productivity in construction. J. Practice Periodical on Structural Design and Construction., 14(2), 81-89.

Dicks, M., (2002). Commissioning management - how to Achieve a fully-functioning building." BSRIA application guide 5/2002. ISBN 0 86022 599-2.

Gibb, A.G.F., (2006) (Keynote). Occupational health: slow accidents need solutions fast, in Fang, Choudry & Hinze (eds), Global Unity for Safety & Health in Construction, Proc. of CIBW99 Int. Conf., June 2006, Beijing, Tsinghua University Press, pp. 22-33.

Goodier, C.I., Gibb, A.G.F., (2005). Barriers and opportunities for offsite in the UK. Systematic Innovation in the Management of Projects and Processes. Abdul Samad Kazi (ed), cib Helsinki international joint symposium, pp. 148-158, ISBN 952 5004 64 3.

Guo, S. J., (2002). Identification and resolution of work space conflicts in building construction. J. Constr. Eng. Manage., 128(4), 287-295.

Hanna, A. S., Peterson, P., and Lee, M-J., (2002). Benchmarking productivity indicators for electrical/mechanical projects. J. Constr. Eng. Manage., 128(4), 331-337.

Hawkins, G., (1997). Improving M&E site productivity, BSRIA technical note TN 14/97, The Building Services Research and Information Association, Bracknell, UK.

Hawkins, G., (2002). Site Productivity – 2002. A guide to the uptake of improvements, BSRIA technical note TN 13/2002, The Building Services Research and Information Association, Bracknell, UK.

Health and Safety Executive, (2000). Backs for the future: safe manual handling in construction, HSE books, Norwich, UK.

Health and Safety Executive, (2007). Health and safety in the construction industry. <http://www.hse.gov.uk/construction/index.htm> (Mar. 4, 2007).

Health and Safety Executive, (2007a). Better backs in construction. <http://www.hse.gov.uk/construction/backs/index.htm> (Mar. 4, 2007).

Health and Safety Executive, (2007b). "Musculoskeletal disorders – HSE and MSD's." <http://www.hse.gov.uk/msd/hsemsd.htm> (Mar. 4, 2007).

Henrich, G., Tilley, P., Koskela, L., (2005). Context of production control in construction. Proceedings of the 13th annual conference of the International Group for Lean Construction, Sydney, Australia.

Horman, M. J., Orosz, M. P., and Riley, D. R. (2006). Sequence planning for electrical construction. J. Constr. Eng. Manage., 132(4), 363-372.

Howell, G., Laufer, A., and Ballard, G. (1993). Interaction between subcycles – One key to improved methods. J. Constr. Eng. Manage., 119(4), 714-728.

Sillanpaa, J., Lappalainen, J., Kaukiainen, A., Viljanen, M., Laippala, P., (1999). Decreasing the physical workload of construction work with the use of four auxiliary handling devices. International Journal of Industrial Ergonomics, no.24, 1999, 211-222.

Thomas, H. R., Horman, M. J., and de Souza, U. E. L., (2004). Symbiotic crew relationships and labor flow. J. Constr. Eng. Manage., 130(6), 908-917.

Wilson, D., (2000). Innovative M&E installation, BSRIA ACT 9/2000, The Building Services Research and Information Association, Bracknell, UK.

Winch, G. M., and North, S. (2006). Critical space analysis. J. Constr. Eng. Manage., 132(5), 473-481.

APPENDIX F BSRIA BEST PRACTICE RECOMMENDATIONS

Scheduled here are the 63 best practice recommendations from Hawkins (1997) for pre-construction phase and construction phase and whether these have been implemented in the Construction System or were done already in CHt. These are presented in table 6.1.

Table 6.1 BSRIA best practice recommendations and whether implemented

No.	Best practice recommendations for pre-construction phase	Whether implemented?
	Contract strategy	
1	"Accurate best practice productivity data should be input to the tendering process".	Yes – done in the System.
2	"Installation contracts should be productivity driven and not price driven, and incorporate an incentive mechanism".	Partially done in the System.
3	"Sub-contracts should be made with those companies employing directly employed labour whose productivity is monitored".	Yes – done already in CHt.
4	"Delegate responsibility only to those parties equipped to own and competently manage the risk".	Yes – done already in CHt.
5	"A mechanism should be in place to optimise the timing of specialist M&E contractor appointments relative to the design development".	Yes – done already in CHt.
6	"The number of levels of sub-contracts should be kept to a minimum".	Yes – done in the System.

No.	Best practice recommendations for pre-construction phase	Whether implemented?
	Project planning	
7	"Accurate best practice productivity data should be input to the planning process".	Yes – done in the System.
8	"The total work scope should be planned in detail.	Yes – done in the System.
9	Adequate tendering and construction lead-in time should be allowed".	Yes – done in the System.
10	"An IT based feedback system relating progress to all resources should be implemented".	Yes – done in the System.
11	"Site management and operatives should be set short-term productivity targets, monitored, controlled and informed of their performance".	Yes – done in the System.
12	"Project objectives should be clearly defined and communicated to all parties involved, including the installing tradesmen".	Yes – done in the System.
	Project organisation	
13	"The M&E site management and operative team members are critical appointments".	Yes – done already in CHt.
14	"Responsibility needs to be defined right through to the installing tradesmen".	Yes – done already in CHt.
15	"An IT based document management system should be employed".	Yes – done already in CHt.
16	"A simple and effective communication system between site operatives and management should be implemented".	Yes – done in the System.
17	"A teambuilding initiative involving site operatives should be implemented".	Yes – done already in CHt.

No.	Best practice recommendations for pre-construction phase	Whether implemented?
	Temporary works	
18	"The provision of a permanent hoist for the movement of materials and labour up and down a building should be carefully evaluated. It should access all levels including plant areas".	Yes – done already in CHt.
19	"The selection of a crane for the unloading and distribution of primary plant and associated plantroom materials should consider site constraints in addition to plant weights".	Yes – done already in CHt.
20	"Storage areas should be planned taking into account the construction schedule and the material transportation system available. They should be secure from theft, weather and mechanical damage and be located so as to cause minimum disruption to the work pattern".	Yes – done already in CHt.
21	"A comprehensive task lighting and power distribution system should be installed".	Yes – done already in CHt.
22	"Site office, toilets, changing and break area facilities should be of good quality, clean and secure from theft. They should be located so as to cause minimum disruption to the work pattern".	Yes – done already in CHt.

No.	Best practice recommendations for pre-construction phase	Whether implemented?
	Services design	
23	"System performance specifications should provide appropriate system solutions".	Yes – done already in CHt.
24	"The preparation of specifications should be undertaken with input from manufacturers, specialist contractors and overseas solutions in order to benefit from innovation".	Yes – done in the System.
25	"A 3D CAD model incorporating an automatic material take-off system that uses labour saving components should be employed. This material database should include supports and sundries".	Yes – done already in CHt.
26	"System layouts should be fully co-ordinated and completed before construction commences".	Yes – done already in CHt.
27	"Layouts and specifications should fully interrelate if the maximum potential is to be gained from the exploitation of innovative systems and components".	Yes – done already in CHt.
28	"Distribution routes should be as linear as possible in plan and elevation".	Yes – done already in CHt.
29	"The M&E design should be fully integrated with structural and architectural systems and components".	Yes – done already in CHt.
30	"Standard terminal pipework and ductwork configurations that employ flexible connections should be employed".	Yes – done already in CHt.
31	"A common support detailing approach should be thoroughly evaluated".	Yes – done in the System.
32	"Installation drawings should be fully dimensioned and detail all installation requirements. This information should be comprehensive, clear and simple to extract".	Yes – done already in CHt.

No.	Best practice recommendations for pre-construction phase	Whether implemented?
	Construction philosophy	
33	"A comprehensive constructability review that involves specialist M&E contractors should promote operation efficiency and good access".	Yes – done in the System.
34	"The designs and specifications presented to site operatives should promote the minimisation of site activities".	Yes – done in the System.
35	"Prefabrication and pre-assembly should be considered".	Yes – done already in CHt.
36	"Standard time saving components and connections should be used".	Yes – done already in CHt.
37	"The quality of types and sizes should be rationalised".	Yes – done in the System.
	Procurement strategy	
38	"Timely supply of specified materials should be ensured".	Yes – done in the System.
39	"An IT based material ordering and tracking system should be employed".	Partially done in the System.
40	"Materials should be identified, sorted and grouped at the point of manufacture and then delivered in a manner that will aid efficient distribution on site".	Yes – done in the System.
41	"Sundries such as nuts, bolts, washers, gaskets, hangers, threaded rod, unistrut, rivets, hemp/PTFE, and boss white should always be available".	Yes – done in the System.
42	"A designated team should be responsible for planning and moving material deliveries to their points of storage and use".	Yes – done in the System.

No.	Best practice recommendations for construction phase	Whether implemented?
	Work arrangement	
43	"The hours actually worked by site operatives should be closely monitored and controlled".	Yes – done in the System.
44	"Gang sizes and organisation of work within gangs demand detailed attention".	Yes – done in the System.
45	"Accurate best practice productivity data should be incorporated into any bonus scheme implemented".	No – Not CHt policy.
46	"Regular guaranteed overtime should be avoided".	Yes – done already in CHt.
47	"Regular toolbox talks discussing productivity, quality, lessons learned and job progress should be undertaken".	Yes – done already in CHt.
48	"Post-qualification training of M&E site operatives with respect to new products, methods and time management should be undertaken".	Yes – done already in CHt.
49	"Site operative training should produce multi-skilled tradesmen".	Yes – done in the System.
50	"A comprehensive system of M&E site operative registration should be implemented".	Yes – done already in CHt.
51	"Two-way radios should be provided for communication between site management, foremen and operatives".	Yes – done already in CHt.

No.	Best practice recommendations for construction phase	Whether implemented?
	Work area control	
52	"Material should be delivered in an orderly manner to the point of use by a designated unskilled crew. It should be only handled once, be clearly identifiable and have installation information attached".	Yes – done in the System.
53	"Material should be palletised or stored on mobile racks with appropriate mechanical and weather protection. Any surplus should be removed as soon as it is no longer required".	Yes – done in the System.
54	"Sundries and small fittings should be stored at the workface".	Yes – done in the System.
55	"A logical sequence of single trade visits to a designated work area is imperative".	Yes – done in the System.
56	"A task should be completed in one visit to a specified workplace".	Yes – done in the System.
57	"There should be designated rubbish collection points and each tradesman should be encouraged to keep the workplace tidy".	Yes – done already in CHt.
	Installation	
58	"Datum's and grids should be agreed between all trades before work commences".	Yes – done in the System.
59	"Working platforms should be available at all times".	Yes – done in the System.
60	"Contractor lifts should be employed for positioning".	Yes – done already in CHt.
61	"Power tools and in particular portable power tools for cutting and fixing should be used at all times".	Yes – done in the System.
62	"Workbenches should be provided".	Yes – done in the System.
63	"Appropriate functional overalls and tool belts should be used".	Yes – done in the System.

Of the 63 recommendations one was not implemented (not CHt policy); two were partially implemented (of which one was done anyway within CHt and one was done because of this research project) and 60 were implemented in the System (of which 29 were done already within CHt and 31 were implemented because of this research project).

APPENDIX G SAFETY RESULTS FROM THE SAMPLE PERIOD

Included here are the 19 minor injuries as reported in CHt's accident reporting system for the case study project. These are presented in table 6.2.

Table 6.2 Safety results from the sample period

Accident No.	Accident Type	Date of Accident	Assign Primary Cause	Summary Details of Accident	Underlying Causations	Behaviours	Injured Body Parts & Injury Type
1	Minor Injury	09-Aug-07	Slip/Trip	On Level 3 CZ8 the operative put his foot in a hole for a shower gulley that was unprotected. The hole was 150mm diameter and had been protected. The reason why the protection was removed was uncertain however in other areas other hole protection had been removed to allow the knocking out of the plastic pipe sleeves and likewise not re-fixed adequately as original method of fixing was nails when slab being cast. The nails were left in the hole and the nail penetrated the top of the boot and injured top of foot.	Miscellaneous / Other	Human Error	Right Foot|Other
2	Minor Injury	05-Dec-07	Handling, Lifting or Carrying	Lifting on new equipment, pin not in fully and trapped finger.	Inadequate Training	Communication Failure	Right Fingers|Superficial Cuts/Abrasions
3	Minor Injury	11-Dec-07	Slip/Trip	Installing drainage pipework and removed hole protection over 150mm hole and later stepped back on a nail in plywood which was left on floor by the injured person.	Miscellaneous / Other	Human Error	Left Foot|Superficial Cuts/Abrasions
4	Minor Injury	13-Mar-08	Handling, Lifting or Carrying	Within the site compound a small portable generator was left in the roadway. Richard moved the generator to allow a van to pass and when setting the generator down trapped his left hand wedding finger under the machine trapping the finger nail. He attended hospital. Separation of nail apparent.	Miscellaneous / Other	Human Error	Left Fingers|Other

Accident No.	Accident Type	Date of Accident	Assign Primary Cause	Summary Details of Accident	Underlying Causations	Behaviours	Injured Body Parts & Injury Type
5	Minor Injury	17-Mar-08	Slip/Trip	Level 3 Maternity Grid 6-7B.A. Tripped over a piece of basket tray on the floor and put his right hand down first to stop him and put it onto a partitioning metal studwork (photo) also on floor. Gloves were being worn however the gloves and hand were cut.	Miscellaneous / Other	Human Error	Right Hand|Superficial Cuts/Abrasions
6	Minor Injury	11-Jun-08	Other	Drilling a section of ductwork in riser 9 Level 4, the drill bit 3/16th broke. The drill moved forward as the drill bit broke and his hand was cut on the side of a piece of ducting. Attended hospital and received stitches before returning to work.	Work Method Poor / Incorrect	Human Error	Right Fingers|Superficial Cuts/Abrasions
7	Minor Injury	11-Jun-08	Handling, Lifting or Carrying	Plantroom 3 Level 5. When separating 2 pieces of ductwork to install a flexible connection caught left hand thumb as separated parts come back together. Was wearing gloves.	Work Method Poor / Incorrect	Personal Factors (carelessness, negligence...)	Left Thumb|Other
8	Minor Injury	12-Jun-08	Handling, Lifting or Carrying	Level 1 Oncology. Pulling in sub-distribution cabling on basket tray, whilst pulling caught arm on a lip of the basket tray cutting arm. Bandaged forearm and returned to work.	Miscellaneous / Other	Personal Factors (carelessness, negligence...)	Right Lower Arm|Superficial Cuts/Abrasions
9	Minor Injury	24-Jun-08	Other	Doorway from level 3 plantroom roof into Level 3 maternity is a reduced height door. Walking through it with helmet on and caught helmet / head on door frame.	Miscellaneous / Other	Human Error	Head|Strain / Sprain
10	Minor Injury	03-Jul-08	Exposure to Harmful Substance	Working on staircase OM3 installing metal conduit. Drilling conduit box with safety glasses small shard of metal got around glass and into eye. Went to hospital to get cleaned out.	Work Method Poor / Incorrect	Personal Factors (carelessness, negligence...)	Eyes|Superficial Cuts/Abrasions

Accident No.	Accident Type	Date of Accident	Assign Primary Cause	Summary Details of Accident	Underlying Causations	Behaviours	Injured Body Parts & Injury Type
11	Minor Injury	07-Jul-08	Contact with Plant / Machinery	The operative was working in ceiling space in room ONCIP20 doing plumbing works and caught his arm on the edge of a basket tray cutting elbow and needing a plaster applying.	Lack of adequate planning	Personal Factors (carelessness, negligence...)	Right Elbow|Superficial Cuts/Abrasions
12	Minor Injury	16-Jul-08	Exposure to Harmful Substance	Walking past loading bay on level 2. Some dust blew into eye around glasses. Went to hospital to clean out and returned to work at 2.30.	Unsafe Place of Work	Non-Compliance with Procedures	Eyes|Superficial Cuts/Abrasions
13	Minor Injury	06-Aug-08	Other	Cutting rod in vice, hand slipped, caught right little finger on vice, gloves were worn.	Miscellaneous / Other	Human Error	Right Fingers Contusion / Bruising
14	Minor Injury	12-Aug-08	Moving / Falling Object	Releasing tube from soffit mounted pendant, tube slipped and impacted right thigh causing minor grazing and bruising.	Work Method Poor / Incorrect	Personal Factors (carelessness, negligence...)	Right Upper Leg Superficial Cuts/Abrasions
15	Minor Injury	19-Sep-08	Slip/Trip	Level 3, zone 7, M&O. While using pipe grips, Chris slipped causing left thumb to get caught between pipe grips and adjustable spanner. Chris was wearing gloves at the time.	Miscellaneous / Other	Human Error	Left Thumb Contusion / Bruising
16	Minor Injury	02-Oct-08	Exposure to Harmful Substance	Level 2, zone 1, ONCDU 037a. Removing leaking w.c. cistern. Cistern contaminated by ball 141 cleaning fluid, melted plastic covering fingers on left and right hands causing irritation and flaking of skin.	Miscellaneous / Other	Non-Compliance with Procedures	Left Hand|Burns
17	Minor Injury	09-Oct-08	Moving / Falling Object	Within the locker room after clocked out for the evening lockers were knocked over and a bench hit the injured party on head. Also an injury to his left heel was reported after the initial report.	Miscellaneous / Other	Human Error	Head|Contusion / Bruising, Left Ankle|Contusion / Bruising

Accident No.	Accident Type	Date of Accident	Assign Primary Cause	Summary Details of Accident	Underlying Causations	Behaviours	Injured Body Parts & Injury Type
18	Minor Injury	15-Oct-08	Moving / Falling Object	Linen store, RADTH116. George was poking the apex wiring through the wall above the ceiling and a part of the ceiling grid fell down cutting George on his right cheek.	Defective Materials / Equipment	Personal Factors (carelessness, negligence...)	Head|Laceration
19	Minor Injury	20-Oct-08	Other	Generator room door along GLG. Whilst going into the generator room, he stepped onto the manhole cover (plastic). The cover was not secured then he fell into the manhole and injured his right leg just under the knee.	Miscellaneous / Other	Personal Factors (carelessness, negligence...)	Right Lower Leg|Contusion / Bruising

APPENDIX H LESSONS LEARNED FROM IMPLEMENTATION

Included here are certain important lessons learned for each of the main elements of the System on the Maternity and Oncology phase together with the change implemented.

H.1 PLANNING AND PRODUCTION CONTROL

Last Planner System was only implemented during the installation phase of the case study project. The problem found was that the team needed more visibility and reliability of the preceding steps i.e. manufacturing, procurement, production drawings and design. On following phases of the overall project LPS was implemented in each of these key steps.

H.2 POSTPONEMENT AND PARTS KITTING

As has been described in this thesis, type B and C components were to be parts kitted for delivery direct to point of use on a call-off basis. For certain components (cast iron drainage pipe and fittings) with low variety (small amount of component type per kit) parts ran out. This was because of errors in either parts kitting or call-offs. The solution to this was too kanban these components using a simple two bin system. When one bin was near to being emptied it was simply replenished therefore avoiding shortages. This is presented in figure 6.1.

Figure 6.1 Mobile kanban unit for cast iron drainage fittings

Certain type C components also ran out at point of use. This included unistrut, screwed rod, nuts and bolts and the like. The solution to this was to design more comprehensive mobile parts centres for each team that was replenished more frequently by the logistics team. This is presented in figure 6.2.

Figure 6.2 Redesigned type C parts centre

H.3 WEEK-BEAT SCHEDULING

Within the agreed Week-Beat construction zone cycle-time not enough periods were allowed for inspection, testing and sign-off before the subsequent trades started their work. The intent was to reduce overall cycle-time but this proved to be too tight in practice as it caused too much working backlog building up to be done later. It also delayed insulation of pipework systems which had to be done out of sequence. The solution to this was to add time back into the Week-Beat sequence for testing (one week – line 12) and inspection and sign-off (one week – line 15). This is presented in figure 6.3 for Hub and Wards MEP1 operations.

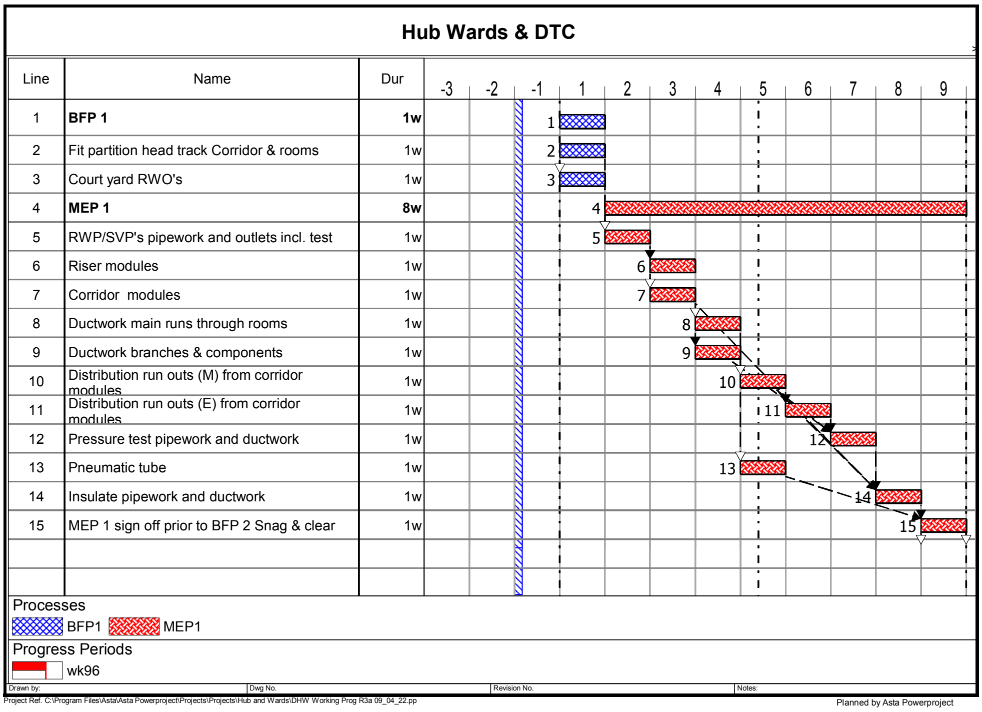

Figure 6.3 **Revised MEP1 operations programme for Hub and Wards**

Also close-scheduling of different trades would not work on operations carried out in the same construction zone in the same week. This was considered to be too tight and relied too much on the exact synchronisation of different work by different teams. Plus too many sets of workers with their mobile work cells occupied the space. The solution to this was not to close schedule operations within a Week-Beat period.

The combination of these two lessons learned increased the overall construction zone cycle-time from 46 to 50[63] weeks but ensures timely completion of construction zones with minimum outstanding working backlog. This means going slower incrementally to go faster overall as completion occurs as you go with no delays occurring needing to be recovered later.

[63] One week added for testing; one week added for inspection and sign-off; one week added to separate the close-scheduled corridor modules and ductwork; and one week added to separate close-scheduled mechanical distribution run-outs with electrical distribution run-outs.